Fisheries and Oceans Canada | Pêches et Océans Canada
Science | Sciences

C S A S | *S C C S*

Canadian Science Advisory Secretariat | **Secrétariat canadien de consultation scientifique**

Research Document 2003/037 | **Document de recherche 2003/037**

Not to be cited without
Permission of the authors * | Ne pas citer sans
autorisation des auteurs *

Analyses of stock and fishery dynamics for cod in 3Ps and 3KL based on tagging studies in 1997-2002.

Analyses de la dynamique de la pêche et des stocks de morue dans 3Ps et 3KL reposant sur des données d'études d'étiquetage menées de 1997 à 2002.

Noel Cadigan and John Brattey

Department of Fisheries and Oceans
Science, Oceans and Environment Branch
P.O. Box 5667
St. John's, NF
A1C 5X1

* This series documents the scientific basis for the evaluation of fisheries resources in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

* La présente série documente les bases scientifiques des évaluations des ressources halieutiques du Canada. Elle traite des problèmes courants selon les échéanciers dictés. Les documents qu'elle contient ne doivent pas être considérés comme des énoncés définitifs sur les sujets traités, mais plutôt comme des rapports d'étape sur les études en cours.

Research documents are produced in the official language in which they are provided to the Secretariat.

Les documents de recherche sont publiés dans la langue officielle utilisée dans le manuscrit envoyé au Secrétariat.

This document is available on the Internet at: | Ce document est disponible sur l'Internet à:
http://www.dfo-mpo.gc.ca/csas/

ISSN 1499-3848 (Printed)
© Her Majesty the Queen in Right of Canada, 2003
© Sa majesté la Reine, Chef du Canada, 2003
Canada

Abstract

We update the analyses in Cadigan and Brattey (2001a, 2002) using additional recaptures from cod tagging experiments conducted in NAFO Divisions 3K and 3L (3KL) and Subdivision 3Ps during 1997-2002. The additional recaptures we consider occurred up to the end of 2002. Using this data we estimate exploitable biomass and fishery exploitable rates, with adjustments for tagging mortality, tag loss, growth and fishery selectivity, stock migrations, and reporting rates. Our methods are similar to those in Cadigan and Brattey (2001a, 2002), although the methods we used to account for fish movements were improved.

We estimated exploitable biomass for three regions in 3KL for weeks in which sufficient landings (>50 tonnes) were reported to get reasonable estimates. Catch-weighted averages (over weeks) of these estimates were 3 000 tonnes for the inshore of 3K, 14 000 tonnes for the northern part of 3L, and 7 000 tonnes for the southern part of 3L. The 2002 total biomass estimate for the inshore part of 3KL was 24 000 tonnes. This was substantially less than the 2001 estimater of 59 000 tonnes. The exploitation rate (landings divided by average exploitable biomass) for 3KL in 2002 was 17%. This increased from 2001 (12%) despite a reduction in the quota from 7 000 tonnes in 2001 to 4 000 tonnes in 2002.

Résumé

De nouvelles données de reprise, s'étalant jusqu'à la fin de 2002, de morues étiquetées dans le cadre d'expériences menées de 1997 à 2002 dans les divisions 3K et 3L et la sous-division 3Ps de l'OPANO ont servi à mettre à jour les analyses de Cadigan et Brattey (2001a, 2002). Ces données ont permis d'estimer la biomasse exploitable et les taux d'exploitation, après correction de la mortalité imputable à l'étiquetage, la perte d'étiquettes, la croissance, la sélectivité des engins, les migrations et les taux de déclaration des prises. Les méthodes appliquées sont semblables à celles de Cadigan et Brattey (2001a, 2002), sauf celles tenant compte des déplacements de la morue, qui ont été améliorées.

On fait aussi des estimations de la biomasse exploitable dans trois secteurs de 3KL pendant les semaines pour lesquelles le niveau des prises déclarées permettait d'obtenir des estimations raisonnables (> 50 t). Les moyennes des estimations, pondéreés en fonction des prises (sur une période de semaines) s'élevaient à 3 000 t pour le secteur côtier de 3K, 14 000 t pour le secteur nord de 3L et 7 000 t pour le secteur sud de 3L. La biomasse totale estimative en 2002 dans les eaux côtières de 3KL se chiffrait à 24 000 t, ce qui est nettement moins qu'en 2001, lorsqu'elle avait été estimée à 59 000 t. Le taux d'exploitation (les prises divisées par la biomasse exploitable moyenne) dans 3KL en 2002 s'élevait à 17 %, soit une augmentation par rapport à 2001 (12 %), malgré une réduction du quota, qui avait été ramené de 7 000 t en 2001 à 4 000 t en 2002.

1 Introduction

Cadigan and Brattey (2001a, 2002) presented methods to estimate exploitation and migrations rates for cod in NAFO Divisions 3KL and Subdivision 3Ps during 1997-2000. The migrations were modelled for eight geographic regions around coastal Newfoundland and the offshore part of 3Ps, based on a simple discrete-time diffusion process. The exploitation rates were estimated as the number of tagged fish caught and reported divided by the number of tagged fish estimated to be available, with adjustments for reporting rates, tagging mortality, and tag loss. The exploitation rate estimates were region, length, and week specific. The rates were combined over length classes using estimated length frequencies of the commercial landings to produce weekly estimates of the total exploitation rates by the fishery.

In this paper we modify and update the analyses of Cadigan and Brattey (2001a, 2002). We extend their analyses using additional recaptures of cod from tagging experiments conducted in 1997-2002. We use information from the tagged cod caught before the end of 2002. We use a more flexible method to account for the movement of tagged cod, and we feel this new method results in more accurate estimates of exploitation rates. The new data we use are described in the next section. This is followed by descriptions of modifications of methods and results in **Section 3**. A short discussion is presented in **Section 4**.

2 The data

We analyze the tag-returns from 118 tagging experiments conducted in 3Ps and 3KL during 1997-2002. An experiment was defined as those fish tagged in the same vicinity during a 1-2 week time period. The number of fish released in each experiment ranged from 57 to almost 4000, with an average of approximately 660. In these experiments over 78 000 fish in total have been tagged, and just over 13 000 tags have been returned from fisheries in these regions and also from fisheries in NAFO Divisions 3N and 3O (3NO), 4R-4S, and Subdivision 3Pn (3Pn-4RS).

We grouped the locations of recaptures into the same geographic regions used in Cadigan and Brattey (2001a). The numbers of fish released in each region are shown in Table 1. The region with the most tagging was 3Ps_PB (Placentia Bay), with 41% of the total number tagged, followed by 3L_INN (Bonavista Bay and Trinity Bay) with 23%. Fewest fish (4%) were tagged in 3K_IN (north of Bonavista Bay, including Notre Dame Bay). The numbers of tagged fish reported caught are shown in Table 2. In each year the numbers are from fish tagged in that year and in previous years back to 1997. Almost 62% of all reported recaptures came from 3Ps_PB, but there have been substantial numbers of recaptures reported for most regions except 3NO.

Table 1. Number of fish tagged and released in each region and year. Note that no fish have been tagged in 3NO or 3Pn+4RS in our experiments.

	Region						
Year	3K_IN	3L_INN	3L_INS	3Ps_PB	3Ps_OF	3Ps_WB	total
1997	259	1565	1529	5969	0	0	9322
1998	118	0	0	5805	1840	2285	10048
1999	1692	4848	1228	4828	1807	1814	16217
2000	397	2381	724	6337	1044	2422	13305
2001	0	5064	875	4326	1240	2797	14302
2002	750	4094	148	4906	1509	3523	14930
total	3216	17952	4504	32171	7440	12841	78124

3 Tagging Model and Estimates

In this section we briefly describe methods and present estimates of exploitation rates and stock size from the tag-recaptures. The results from several separate analyses are combined to estimate exploitation rates. The steps are described in the following sections.

Table 2. Number of tagged fish reported captured.

	Region								
	3K_	3L_			3Ps_			3Pn_	
Year	IN	INN	INS	3NO	PB	OF	WB	4RS	total
1997	1	5	10	2	343	1	13	0	373
1998	32	57	88	3	720	25	130	22	1077
1999	477	321	138	1	2040	40	221	36	3275
2000	129	345	85	2	2040	57	262	18	2938
2001	122	640	228	3	1816	44	240	45	3138
2002	88	724	49	1	1062	44	212	31	2211
total	849	2092	598	11	8021	211	1078	152	13012

3.1 Reporting rates and tag loss rates.

One of the first steps when analyzing tag-recaptures is to estimate reporting rates and tag loss rates. Reporting rates are required to infer the number of tagged fish that were caught but not reported. Tag loss rates are required to estimate the size of the tagged population available to the fishery. We used the methods described in Cadigan and Brattey (2004) to estimate reporting rates and tag loss rates simultaneously. These methods are briefly summarized as follows.

Several types of tags are used in many of our experiments. Typically 10-20% of the tags used are high-reward tags, and the reward value ($100 Can.) is sufficient that we can assume virtually all of these tags on captured cod are returned. Using this reference value we can estimate the reporting rates of the more commonly used low reward tags.

Also, some fish are double tagged and this allows us to estimate the tag loss rate using information from the number of double tagged fish that are recaptured with only one tag. We used Kirkwood's (1981) parametric model for tag loss rates,

$$\log\{\Phi(t)\} = \beta_o \log\left(\frac{\beta_o}{\beta_o + \beta_1 t}\right);\ \beta_o, \beta_1 \geq 0,$$

where $\Phi(t)$ is the cumulative probability that a tag is retained on a fish after time t since release. Cadigan and Brattey (2004) showed that this model fitted their cod data (a subset of the data we examine in this paper) significantly better than the more traditional proportional tag loss model $\log\{\Phi(t)\} = -\beta t$. Also, Kirkwood's model fit their data as well as a very flexible nonparametric estimator and this suggested that further improvements in fit are unlikely by using more complicated parametric models. The loss rates are estimated separately for the two positions around the dorsal fin that are tagged (i.e. positions 1 and 2 for front and back). Note that tags on single tagged fish are attached at position 1. We also estimated the reporting rates separately for single and double tags because fishermen received twice the reward for returning two tags from a double tagged fish.

We estimated reporting rates each year because ancillary information suggested that reporting rates may have changed over time, although we have no reason to expect that the reporting rates would change within a year because of the tendency for many fishermen to batch-mail the tags they acquired each year. We pooled estimates for 1997 and 1998 because of the small number of tags returned in 1997 (see Table 2). We also estimated reporting rates separately for three geographic regions: 3KL, 3Ps + 3NO, and 3Pn_4RS. We choose these regions as a minimal number to account for regional differences in reporting rates. The linkages between fishermen within these regions are much stronger than between the regions. There was insufficient data to estimate annual reporting rates in 3Pn_4RS so we estimated only constant reporting rates during 1997-2002 for this region.

The tag loss rates are shown in Figure 1. The differences in the loss rates at position 1 and 2 were shown to be very significant in Cadigan and Brattey (2004). After five years we estimate that 82% of the tags in position 2 are still retained, whereas only 70% of the tags in position 1 are retained. Residual analyses similar to those in Cadigan and Brattey (2004) did not suggest any lack-of-fit for our tag loss rate model. We speculate that the reason for the differences in the tag loss rates is related to encounters with gillnets, which are the most common gear type used in Newfoundland cod fisheries during 1997-2002. Many cod caught for tagging show scarring evidence of previous gillnet entanglements. When this occurs we feel that it is more likely that the tag at position 1 may be dislodged because the girth of the fish is greatest at this position.

Reporting rate estimates are shown in Table 3. The annual differences are significant, although the regional differences are not. The estimates for double tags are almost always higher than for single tags. In the one exception (2002-3Ps+3NO) the estimates were constrained to be equal. The temporal trends in the reporting rates for 3Ps+3NO are consistent with our understanding of what was occurring in the fishery. The trends for 3KL are less consistent; that is, we have no reason to expect that reporting rates

decreased in 2000 compared to 1999, and then increased again in 2001. This requires further investigation; nonetheless, the results are based on an objective criteria and were judged to be reasonable to use in our tagging analyses. The standard errors in Table 3 give a measure of precision for the estimators; however, they may not be useful for confidence intervals. For this purpose we recommend profile likelihood methods. Note that standard errors can not be provided for estimates at their boundary values.

Table 3. Reporting rate estimates (%) and standard errors (in parentheses).

	Single		Double	
Year	3KL	3Ps+3NO	3KL	3Ps+3NO
1997-98	60.3 (13.3)	66.8 (5.65)	70.1 (16.4)	76.7 (6.77)
1999	85.0 (9.09)	71.9 (4.43)	91.4 (11.8)	82.3 (5.93)
2000	66.1 (10.9)	85.6 (6.64)	79.1 (15.0)	93.8 (8.33)
2001	100 (−)	88.2 (9.42)	100 (−)	90.5 (11.9)
2002	65.6 (7.39)	82.3 (10.0)	67.4 (17.6)	82.3 (10.0)

The reporting rate estimates and standard errors (in parentheses) for 3Pn_4RS are 54.8% (11.3%) for single tags and 95.8% (25.5%) for double tags. The low reporting rate for single tags is reasonable because in that region the tagging program has been run concurrently with another tagging program that does not offer direct tag rewards, and this usually results in lower return rates. Although the double tag estimate seems high the standard error is large suggesting that more reasonable values for this reporting rate are also consistent with our data.

3.2 Growth Increments

We require estimates of the lengths of fish at capture because our exploitation rate model accounts for the length selectivity of the fishery. As fish grow they can become more (or less) available to the various gears that are used in the commercial fisheries for cod. Not accounting for growth can result in seriously biased estimates of exploitation rates.

The method we used to estimate growth rates involves a nonparametric version of the Von Bertalanffy model (VONB), which is described in Cadigan and Brattey (2001b). Consider a fish that is length l_r when released at time t_r. The VONB model for the length at capture at time t, $L(t)$, is

$$L(t) = l_r + (\lambda_\infty - l_r)\left\{1 - e^{-K(t,t_r)}\right\}, \tag{1}$$

where $K(t,t_r) = \int_{t_r}^{t} k(u)du$, $k(t)$ is the instantaneous growth rate at time t, and λ_∞ is the asymptotic size that can be attained. A common model used for the growth rate is $k(u) = \kappa$ where κ is a parameter to estimate; however, evidence from the cod tagging

data suggests that growth rates vary between and within years. We adjust for this by using a nonparametric approach for modelling $K(t, t_r)$. This is described in Cadigan and Brattey (2001b).

Empirical evidence from the cod growth increment data suggests that the lengths-at-capture reported by commercial fishermen are biased. This evidence comes from length measurements for cod that are recaptured a short while after release for which little or no growth should occur and the recapture lengths should equal the release lengths. However, we observe a bias that depends on fish size, and this bias is important to account for when estimating growth increments. We use a parametric function to model the bias for a length l fish,

$$b(l) = \alpha_o + \frac{\alpha_1 \exp(l - \alpha_2)}{1 + \exp(l - \alpha_2)}. \tag{2}$$

If $l_{\min} - \alpha_2 << 0$ and $l_{\max} - \alpha_2 >> 0$ then $b(l; \alpha_o, \alpha_1, \alpha_2)$ ranges from α_o to $\alpha_o + \alpha_1$ with an inflection at α_2. This is the basic behavior of the empirical bias evidence presented in Cadigan and Brattey (2000, 2001b). We estimate the bias and VONB parameters using least squares, where the expected value of a capture length at time t, i.e. $Y(t)$, is given by $E\{Y(t)\} = L(t) + b\{L(t)\}$, where $L(t)$ is given by (1) and $b\{L(t)\}$ is computed using (1) and (2).

The parameters of the growth model are straight-forward to estimate. In Figure 2 we illustrate some of the growth predictions using the estimated version of (1). The estimates appear to be reasonable. Small cod (e.g. 50 cm) are estimated to grow approximately 5-6 cm per year, whereas larger cod (e.g. 80 cm) are estimated to grow only 3-4 cm per year. For estimation we constrained $\lambda_\infty > 140$ cm because this is the largest fish we have observed. The estimated λ_∞ is constrained by this bound. We use the growth model to estimate the length distribution of each experiment for every week following release, and up to the end of 2002. For estimating exploitation rates we pooled information for fish greater than 90 cm because we feel that beyond this size there is little length selectivity in the cod fisheries.

Preliminary analyses suggested that the bias in length measurements has varied from year to year; hence, we estimated the parameters in (2) separately each year. The estimated bias functions are shown in Figure 3. The annual differences are statistically significant. The bias functions are consistent with the trends we find in reported growth increments of fish caught soon (< 5 weeks) after release. With no bias we would expected the reported growth increments to be close to zero on average; however, the trends we observe are similar to those in Figure 3.

A variety of residual analyses did not reveal any serious departures in models assumptions. However, there are known problems with the approach we have used for estimating growth increments. The problems involve the effects of between individual variation in growth rates and also temporal variations in growth rates. We feel these processes are no less important for the cod stocks we have considered compared to other stocks. We have other information, primarily some ages at capture and age-length keys for some experiments, that we can utilize to try and address these problems. This is a useful area for future research. There is also some evidence of geographic variations in growth rates, and

this requires further investigation as well. We do not feel that these problems invalidate our results because our methods to estimate exploitation rates are somewhat robust to the growth increments; however, if the estimated growth rates are used for other purposes then some caution should be exercised.

3.3 Selectivity

If the length distribution of the tagged population is different from the length distribution of the exploited population then the selectivity of the fishery must be considered when estimating total (i.e. for all lengths) exploitation rates. Cadigan and Brattey (2000; pg. 8) provided a simple illustration of this. In our experiments cod are caught for tagging primarily using handlines whereas the commercial fishery uses mainly gillnets. The selectivity of these two gears are substantially different; hence, even without growth the length distributions of the tagged populations and the populations available to the commercial fishery are different. In this section we describe how to estimate the length selectivity of the various commercial gears used to capture cod.

The basic equation we use to model tag-recaptures is

$$E(R_{xglti}) = \mu_{glti} q_{xti} M_{xtl}, \tag{3}$$

where R_{xglti} is a random variable for the tagged fish from experiment x and length class l that are recaptured with gear type g at time t and in region i. The unknown exploitation rate is denoted by μ_{glti} and q_{xti} is the fraction of the total survivors from experiment x that are found in region i at time t. We assume that this fraction is the same for all sizes that are exploited. The total number of fish from experiment x that have survived and retained their tags is M_{xtl}. We can estimate M_{xtl} using the known number released, an assumed annual natural mortality rate ($m = 0.2$), and tag loss and reporting rate estimates (see **Section 3.1**). To estimate M_{xtl} we use a simple population decay model, which is described in Cadigan and Brattey (2001a).

We use a separable model for μ_{glti},

$$\mu_{glti} = \mu_{gti} s_{vl}, \tag{4}$$

where s_{vl} is the length selectivity for a gear-region-time category, v. We constrain $\max_l s_{vl} = 1$ so that μ_{gti} is the fully selected exploitation rate. In this section we focus on estimating s_{vl}. The selectivity categories (v's) are listed in Table 4. We estimated a common selectivity for all years. Also, a common ottertrawl selectivity is applied in all regions, although most of the ottertrawl-caught tags came from 3Ps (197) and in particular 3Ps_OF (155). We picked gear and region categories to reflect our understanding of variations in gear selectivity but also so that each category had a reasonable sample size for estimation.

Table 4. Selectivity categories and number of recaptures.

	Region		
Gear	3KL	3Ps+3NO	3Pn_4RS
gillnet	2446	6721	33
handline	503	485	29
linetrawl	60	761	55
other	109	79	-
ottertrawl		205	
trap	137	181	-
unknown	280	894	33

We estimated selectivities using the distribution of R_{xglti} conditional on the total $R_{xgti} = \sum_l R_{xglti}$. We assumed this distribution is multinomial with cell probabilities,

$$\Pr\left(R_{xglti}|R_{xgti}\right) = \frac{\mu_{glti}q_{xti}M_{xtl}}{\sum_l \mu_{glti}q_{xti}M_{xtl}} = \frac{s_{vl}M_{xtl}}{\sum_l s_{vl}M_{xtl}}. \tag{5}$$

We can estimate the M_{xtl}'s without specifying s_{vl} so the only unknowns in (5) are the s_{vl}'s. We used a parametric model for s_{vl},

$$\log(s_{vl}) = \beta_{1v}l + \beta_{2v}l^2,$$

with the constraint $\max_l s_{vl} = 1$. We used maximum likelihood to estimate the β's. For simplicity we have ignored reporting rates, although our methods apply as long as the reporting rates do not depend on length which is reasonable for our data. To simplify our analyses we used 3 cm length classes, whereas in previous studies (e.g. Cadigan and Brattey, 2001a; 2002) we used 1 cm length classes.

The results are shown in Figures 4-9. They are similar to estimates given previously in Cadigan and Brattey (2001a; 2002). In the next section we use these estimates to compute the fully selected exploitation rates in (4).

The appropriateness of the simple parametric selectivity model was examined in Cadigan and Brattey (2001a). They also examined a nonparametric method and found that when the sample sizes were large then the parametric and nonparametric estimates agreed fairly closely. When the samples sizes were small then disagreements were found, and in these cases the parametric estimates seemed preferable. Overall the analyses in Cadigan and Brattey (2001a) suggested that the log-quadratic function is useful for modeling selectivity in the cod fisheries we examined.

3.4 Exploitation and movement rates

In previous steps we have estimated reporting rates, tag loss rates, and length selectivities. Using these estimates we can pool recaptures over tag-types and lengths. The model for the pooled recaptures is

$$E(R_{xgti}) = \mu_{gti}q_{xti}M_{xgti}, \tag{6}$$

where $M_{xgti} = \sum_l s_{vl} M_{xtl}$ and v is the corresponding gear-time-region selectivity category. Equation (6) is simply (3) summed over lengths. We pooled over tag-types for (3); that is, $M_{xtl} = \sum_k \lambda_k M_{xtlk}$ where k indexed the tag-types (see Cadigan and Brattey, 2003) and λ_k was the corresponding reporting rate. The results in the previous sections can be used to estimate the M_{xgti}'s. The unknowns in (6) are the μ's and q's. The final step is to estimate the fully selected exploitation rates (μ_{gti}'s) and the movement parameters (q_{xti}'s). Recall that q_{xti} is the fraction of the total survivors from experiment x that are found in region i at time t. Cadigan and Brattey (2002) used a simple Markov diffusion model for q_{xti}. For each experiment (x) this involved estimating 18 parameters. They used an iterative process to estimate the μ's and q's. Some difficulties became apparent with this approach, and in this paper we use different methods to address these difficulties.

There were two problems with the Markov diffusion model used by Cadigan and Brattey (2002). The first problem was that many of the tagging experiments involved low numbers of releases and subsequently low numbers of recaptures. In this situation the maximum likelihood estimates of q's tended to place most of the fish in the region(s) with low exploitation rate estimates regardless of the release region. For example, when there are zero returns the likelihood is maximized when $q = 1$ for the region with the lowest value of $\mu \times M$ and this tended to be the region with the lowest value for μ because M varies only a little between regions; that is, between regions M differs only because of differences in gear selectivity between regions. Such as solution often does not seem sensible, and the maximum likelihood estimator requires further investigation. The other problem was that the Markov diffusion model, even though it had 18 parameters, often did not seem flexible enough to model the spatio-temporal patterns in tag-recaptures that we observed. The model was also time-consuming to estimate.

In an attempt to improve the movement modelling for the 2003 stock assessment of cod in 3KL we decided to switch to a more basic "compartment-type" movement model and use a different method of estimation. The movement model simply assumed that different subsets of experiments had the same probability of occurrence each year. In one run of our model we assumed that all experiments released in a region in year t had the same q_i's ($i = 1, ..., 8$ for the 8 regions) in years $t, t+1, ..., 2002$. The q's were estimated separately each year. For example, we estimated 7×6 movement parameters for the 1997 experiments in 3K_IN. Only 7 q parameters are estimated each year for the 8 regions because $\sum_i q_i = 1$. This is a substantially simplified approach compared to Cadigan and Brattey (2001a; 2002) where the movements were estimated separately for each experiment using a diffusion model in which between-year variations in q's gradually diminished. We used the same iterative procedure to estimate the μ's and q's; however, we used conditional maximum likelihood for the q's.

Let z denote the set of experiments conducted in a region and in a given year. Let R_{zyi} denote the corresponding pooled (over x, g and t) recaptures and let $D_{zyi} = \sum_{t \in y} \sum_g \sum_{x \in z} \mu_{gti} M_{xgti}$. If the μ's are taken as known then the conditional (on $R_{zy} =$

$\sum_i R_{zyi}$) mle of q given $R_{zy} > 0$ is

$$\hat{q}_{zyi} = \frac{R_{zyi} D_{zyi}^{-1}}{\sum_{i=1}^{8} R_{zyi} D_{zyi}^{-1}}.$$

This is a simple estimator to compute but it is undefined for years with no returns (i.e. $R_{zy} = 0$). In these cases we simply set $q_{zyi} = 1$ for $i \in z$ and zero otherwise; that is, we assume all tagged fish are in the region they were released in for years with no returns from the z set of experiments. This is quite different from Cadigan and Brattey (2002) where the estimator favored putting tagged cod in the region with the lowest exploitation rate when there were no reported recaptures.

Having estimated the movement parameters we simply pool returns for all experiments to estimate the fully selected exploitation rates; that is,

$$\hat{\mu}_{gti} = \frac{\sum_x r_{xgti}}{\sum_x \hat{q}_{zyi} M_{xgti}}, \tag{7}$$

where z is the corresponding set with $x \in z$, and y is the year that corresponds to t. The divisor in (7) is just the estimate of the number of tagged fish in region i during week t, adjusted for reporting rates, that are available to gear type g (i.e. scaled by selectivity). After a few iterations the estimates of μ's and q's do not change much. We repeated the iterations 10 times to produce final estimates. Our procedure involves using simple estimators for a large number of parameters.

As in previous analyses we fixed the annual exploitation rates in 3Pn_4RS and 3NO. This was because cod have not been tagged recently in 3NO, and we do not have data from tagging studies conducted in 3Pn_4RS. The problem caused when some areas do not have tagged releases is that we cannot differentiate between low exploitation/high movement rates and high exploitation/low movement rates. We fixed exploitation rates at values derived after consulting with stock assessment scientists for 3NO cod and 3Pn+4RS cod. The values we choose for the fully recruited exploitation rates were $\mu_{97} = 0.045$, $\mu_{98} = 0.05$, $\mu_{99} = 0.08$, $\mu_{00} = 0.098$, $\mu_{01} = 0.09$ and $\mu_{02} = 0.09$ for 3NO cod, and $\mu_{97} = 0.35$, $\mu_{98} = 0.2$, $\mu_{99} = 0.4$, $\mu_{00} = 0.38$, $\mu_{01} = 0.5$ and $\mu_{02} = 0.43$ for 3Pn_4RS cod. These values were applied equally for all weeks and gear types (i.e. 52 weeks $\times$ 7 gears = 364). For example, in 3Pn_4RS $\mu_{gti} = 0.35/364 = 0.0962\%$ for each week during 1997. Previous analyses have suggested that our estimates of exploitable biomass in 3Ps and 3KL are not that sensitive to assumptions about exploitation rates in 3NO and 3Pn_4RS.

Another factor we have adjusted for is short-term tagging mortality. This has been considered in-depth by Brattey and Cadigan (2004). They concluded that average tagging mortality was approximately 13%. We applied this level in our analysis; that is, the number of fish that survived tagging was assumed to be 87%.

3.5 Base run: m=0.2

In this run of our model we assumed that the annual natural mortality was $m = 0.2$; that is, each year $\exp(-0.2) = 82\%$ of the population survived other sources of deaths than the

estimated anthropogenic removals. This is a standard assumption used when assessing cod stocks.

Weekly estimates of fully selected exploitation rates (e.g. μ_{gti}'s) are shown in Figures 10-13. We only show estimates for 2001-2002. Results for 1997-2000 are similar to those in Cadigan and Brattey (2001a; 2002). It is important to note that the weekly bar totals are not estimates of the fully selected total exploitation rates each week. The bars represent estimates of the fully selected exploitation rates for each gear type and because different gears have different fully selected lengths (see Figures 4-9) the results are not additive.

Gillnets are the dominant gear type used in 3KL and in the inshore parts of 3Ps, as is evident in Figures 10-13. In 3KL the highest exploitation rates occurred in late July to early August, which corresponds to when most of the landings occurred. In 3Ps the fishery is spread throughout the year but with minimal activity during March and April (see Figures 12-13).

The probability of occurrence estimates (q's) are shown in Figures 14-36. We did not present results for 2002 releases because these fish were usually recaptured in the same region they were released in, with the exception of 3L_INS releases where most recaptures were from 3Ps_PB. Only very small fractions of the tagged fish in the 1999 and 2001 experiments in 3Ps_OF were estimated to move to other regions, and these results are not presented either. The 1997 and 1998 tagging experiments in 3K_IN suggested considerable mixing with 3L_INN (see Figures 14 and 15), although the number of releases (see Table 1) and subsequent number of recaptures for these experiments was small. Less mixing seems to have occurred in 1999 and 2000 (see Figures 16 and 17). Note that no tagging was performed in 3K_IN in 2001. Fish tagged in 3L_INN were not often recaptured outside of this region (see Figures 18-21), with only small fractions estimated to be found in 3K_IN. However, the 2000 releases suggested that 40% of the survivors were in 3Ps_OF in 2002 (see Figure 20). Although only three fish were recaptured in 3Ps_OF, the low exploitation rates estimated there (see Figures 12 and 13) suggest that a substantial number of fish must have moved there to produce this number of recaptures. We examine this result again in the next section. Note that no tagging was performed in 3L_INN in 1998.

The results in Figures 22-25 suggest that fish tagged in 3L_INS spend most of their time in the adjacent 3Ps_PB region. It is thought that most of the fish tagged in 3L_INS are actually 3Ps fish on feeding migrations. Although only small numbers of 3L_INS tagged fish have been recaptured in 3Ps_OF, our results also suggest that large fractions of 3L_INS tagged fish can sometimes be found in 3Ps_OF. The low exploitation rates in 3Ps_OF seem to have a large effect on some of the associated movement estimates, and they require further investigation (see **Discussion**). We estimate that most fish tagged in 3Ps_OF stay there, although in some years small fractions of these fish are estimated to be available to the fisheries in other regions (see Figures 26 and 27). In 1999, 2001, and 2002 even larger fractions of the 3Ps_OF releases were estimated to stay in this region (results not shown). The majority of fish tagged in 3Ps_PB stay in that region, although relatively small numbers do move to 3Ps_WB, 3Ps_OF, and to a less extent 3L_INS (see Figures 28-32). Substantial numbers of fish tagged in 3Ps_WB are estimated to move

to 3Ps_PB, and fewer numbers move to 3Ps_OF and 3Pn_4RS in 1998 and 1999 (see Figures 33 and 34). Less movements occurred in 2000-2002 (see Figures 35 and 36).

Some of the results in Figures 14-36 suggest that the base run of our model is seriously mis-specified. For example, the predicted tag-recaptures shown in Figure 14 are greater than the observed values in 1999-2002. To investigate this further we examined model residuals plots, which are shown in Figures 37-42. We did not plot residuals for regions where the movements were estimated to be very low. The general pattern is that the model tends to over-predict recaptures after 1-2 years at liberty. For example, in the top panel of Figure 37 the model substantially over-predicts the 2002 recaptures from releases in 1997-2001. Note that numbers are plotted on the square root scale. The absolute deviations are much larger and difficult to plot. The same pattern occurs in 2001 in 3K_IN, and in other regions and years with the exception of 3Ps_OF. This is most consistent with a mis-specification of natural mortality (m), although other factors such as variations in tagging mortality could also cause the discrepancies, albeit in a less obvious manner. In the next section we present a model in which m has been adjusted to reduce the residual patterns. This provides evidence that natural mortality is different from 0.2 in some areas and years.

For comparison purposes it is useful to present estimates of total exploitation rates and exploitable biomass based on the $m = 0.2$ formulation. The purpose of our analyses was to provide estimates of stock size for the assessment of cod in 3KL, and due to time constraints we did not estimate stock size for 3Ps; hence, we only computed estimates of exploitable biomass for the three regions in 3KL. We first review the method we used to aggregate our length-based exploitation rates to produce total exploitation rates.

The total exploitation rate at length is just the sum of exploitation rates by gear types; that is,

$$\mu_{lti} = \sum_g \mu_{glti}.$$

The only reason we considered gear types was to use the separable selectivity model to reduce the dimension of μ_{lti}.

To compute total exploitation rates for all lengths we need information about the length composition of the landings. The total exploitation rate is defined as

$$\mu_{ti} = \frac{C_{ti}}{N_{ti}} = \frac{\sum_l C_{lti}}{\sum_l N_{lti}},$$

where N_{ti} is the total exploited population size and C_{ti} is the total catch (in numbers) in week t for region i. The definition of μ_{lti} is $\mu_{lti} = C_{lti}/N_{lti}$; hence, $N_{lti} = C_{lti}/\mu_{lti}$ and

$$\mu_{ti} = \frac{\sum C_{lti}}{\sum_l C_{lti}/\mu_{lti}} = \frac{1}{\sum p_{lti}/\mu_{lti}},$$

where $p_{lti} = C_{lti}/\sum_l C_{lti}$. To estimate μ_{ti} we need estimates of the length distribution of the catch (i.e. the p_{lti}'s).

It is usually more convenient to estimate stock size in weight rather than numbers. We can also estimate a biomass-based exploitation rate which is defined as $\mu^b_{ti} = Y_{ti}/B_{ti}$ where Y_{ti} is the total landings (yield) by the fishery and B is the exploited biomass. We obtained weekly landings from the quota monitoring program for the fisheries in 3KL and 3Ps. The exploited biomass estimate is $\hat{B}_{ti} = \sum_l \hat{B}_{lti} = \sum_l Y_{lti}/\hat{\mu}_{lti}$ and $\hat{\mu}^b_{ti} = Y_{ti}/\hat{B}_{ti}$.

We estimate the landings at length, Y_{lti}, using Y_{ti} and estimates of the proportions caught at length for each gear type,

$$p_{glti} = \frac{C_{glti}}{\sum_l C_{glti}}.$$

These proportions are obtained using the methods in Healey and Cadigan (2001). The estimated landings-at-length are given by

$$Y_{lti} = \sum_g Y_{gti} \left\{ \frac{w(l)p_{glti}}{\sum_l w(l)p_{glti}} \right\},$$

where $w(l) = \exp(3.0879 * \log(l) - 5.2106)/1000$ is the standard weight-length relationship used for cod in 3Ps and 3KL.

The weekly landings and estimates of $\hat{\mu}^b_{ti}$ and $\hat{B}_{ti}$ for 1999-2002 are presented in Figures 43-46. The averages at the top of the bottom panels are catch-weighted averages of the weekly biomass estimates for weeks in which at least 50 tonnes were landed. The annual total exploitation rate estimates presented along the top of the middle row panels are the total landings (for all weeks) in each region divided by the catch-weighted average exploitable biomass estimates. We consider these results further at the end of the next section.

3.6 Preferred run

The structure of the model for our preferred run was derived from an ad hoc iterative procedure in which adjustments were made to m, the model was re-run, and the residuals were assessed for trends and goodness-of-fit. In the future we hope to estimate m in a more rigorous manner. The structure we selected for m is shown in Table 5. The value for 3K_IN (i.e. $m = 0.8$) is very high, but may be realistic given the reports of large scale mortality due to freezing and seal predation that have been reported for cod in that region.

Table 5. Values for natural mortality, m, used in the final tagging model.

Region	m
3K_IN	0.8
3L_INS, 3L_INN	0.4
3Ps_OF, 3Ps_PB, 3NO	0.3
3Ps_WB, 3PN_4RS	0.4

The residual plots analogous to Figures 37-42 are presented in Figures 47-52. A high level of m in 3K_IN was required to reduce the residual patterns in Figure 37. The results in Figure 47 are substantially improved, although our preferred model still cannot account for the decline in 3K_IN tag-recaptures in 2002 from the 1999 and 2000 releases in 3K_IN. The residuals for 3L_INN (compare Figures 38 and 48) and 3L_INS (compare Figures 39 and 49) are substantially improved, although further adjustment of m for 3L_INS may still be warranted. We could not substantially improve the residuals in 3Ps_OF by adjusting m (compare Figures 40 and 50). Small improvements in the residuals for 3Ps_PB were made by adjusting m to 0.3 (compare Figures 41 and 51, especially the 3Ps_PB panel). The residual patterns were also improved for the 3Ps_WB releases (compare Figures 42 and 52), although further improvements may still be possible.

The estimates of the probability of occurrence (i.e. q's) were very similar to those presented in the last section. The average difference over all release regions and years ranged from 0.15% for 3Pn_4RS to 1.8% for 3Pn_PB. For example, the results shown in Figure 53 are similar to those shown in Figure 20. The estimate of the fraction found in 3Ps_OF decreased from 40% to 34% with the m modifications.

Estimates of average annual exploitable biomass and exploitation rates are shown in Figures 54-57. A summary of these results and those in the previous section is presented in Table 6. Clearly the higher values for m have considerable impact on the biomass and exploitation rate estimates, especially in 3K_IN where the change was the greatest. The biomass estimates in our preferred run increase from 43 Kt in 1999 to 60 Kt in 2001, but then decline to 24 Kt in 2002. The reported total landings in 2002 for 3KL was 4 Kt, which is 17% of the estimated exploitable biomass.

Table 6. Average annual exploitable biomass and exploitation rates from the preferred run and the $m = 0.2$ run (in parentheses).

		Region			
	Year	3K_IN	3L_INN	3L_INS	3KL
Exploitable Biomass (Kt)	1999	8.1 (9.1)	31.1 (31.9)	3.7 (4.9)	42.9 (45.8)
	2000	13.6 (39.1)	27.6 (37.8)	6.1 (10.6)	47.3 (87.5)
	2001	23.9 (57.6)	32.3 (39.7)	2.9 (2.3)	59.1 (99.6)
	2002	2.9 (7.3)	14.2 (20.8)	6.8 (14.1)	23.9 (42.3)
Exploitation Rates (%)	1999	44.9 (40.1)	10.1 (9.9)	44.8 (33.9)	19.7 (18.4)
	2000	10.8 (3.7)	10.6 (7.7)	17.4 (10.0)	11.5 (6.2)
	2001	7.4 (3.1)	11.1 (9.0)	51.9 (66.5)	11.6 (6.9)
	2002	21.6 (8.5)	18.7 (12.7)	12.9 (6.9)	17.4 (9.8)

These results have been aggregated over lengths, but it is also useful to examine the estimated length compositions of the exploited population in each region. These results are plotted in Figures 58-60 for 2002 only. The length compositions are based on $\hat{N}_{lti} = \hat{C}_{lti}/\hat{\mu}_{lti}$. They are useful for diagnostic purposes because the total exploited abundance is estimated as $\sum_l \hat{N}_{lti}$, and the validity of the total estimate depends on the validity of the length-based estimates. Within-year variations in the length compositions

are caused by variations in catch sampling fractions (p_{lti}'s) and/or variations in $\hat{\mu}_{lti}$'s caused by changes in gear compositions. The average length for all weeks is shown at the top of each figure. The average is weighted by estimated numbers. These results suggest that larger fish were available to the fishery in 3L_INN than in 3K_IN or 3L_INS.

3.7 Q sensitivity run

Our model has a large number of parameters to account for the complexity of the fishery and stock dynamics for cod in 3KL and 3Ps. However, many of these parameters are poorly estimated. We have attempted to use simplifying assumptions where reasonable, such as the separable fishery selectivity model. Our movement model is also a gross simplification of what is occurring in the population, although we feel that it is a reasonable model for estimating exploitation rates. The movement model still requires a large number of parameters to estimate, as was evident in Figures 14-36. In this section we utilize an even simpler approach to account for fish movements. These results are presented as a measure of the potential sensitivity of the estimates in the last section to poorly determined parameters.

In this run we estimate aggregate q's for all release years; that is, we assume that fish released in region i have the same probability of occurrence in subsequent years independent of the year the fish were tagged. This increases the number of recaptures that can be used to estimate the q parameters. Further research is required to assess if this is a useful simplification; however, it is at least useful as a sensitivity analysis.

The estimates of average annual exploitable biomass and exploitation rates are presented in Table 7. In most years and regions the estimates from the sensitivity run are similar to those from the preferred run; however, significant differences do exist. These are identified with a * in Table 7. Methods to account for uncertainty in biomass estimates that results from fish movements requires further investigation.

Table 7. Average annual exploitable biomass and exploitation rates from the preferred run and the sensitivity run (in parentheses).

		Region			
	Year	3K_IN	3L_INN	3L_INS	3KL
Exploitable Biomass (Kt)	1999	8.1 (8.0)	31.1 (31.7)	3.7 (5.60)*	42.9 (45.3)
	2000	13.6 (13.0)	27.6 (27.8)	6.1 (6.8)	47.3 (47.7)
	2001	23.9 (29.3)*	32.3 (30.7)	2.9 (3.9)	59.1 (63.9)
	2002	2.9 (2.9)	14.2 (14.0)	6.8 (4.2)	23.9 (21.1)
Exploitation Rates (%)	1999	44.9 (45.4)	10.1 (9.9)	44.8 (29.8)*	19.7 (18.6)
	2000	10.8 (11.3)	10.6 (10.5)	17.4 (15.5)	11.5 (11.4)
	2001	7.4 (6.0)	11.1 (11.7)	51.9 (39.1)	11.6 (10.8)
	2002	21.6 (21.4)	18.7 (19.0)	12.9 (21.1)*	17.4 (19.7)

4 Discussion and Conclusions

Our aggregate results for 3KL suggest that total exploitation rates increased from 11.5% in 2001 to 17% in 2002, although the landings by the commercial fishery decreased from 7 Kt in 2001 to 4 Kt in 2002. This increase in exploitation occurred in spite of the drop in landings; hence, our estimate of the biomass available to the fishery dropped dramatically in 2002. Estimates from the preferred formulation of our tagging model suggest a small stock size (<60kt) available to the fishery in 3KL over the past four years. In addition, most of the fish appear to be increasingly concentrated in southern Bonavista Bay and western Trinity Bay (Brattey and Healey 2003).

Our analysis of tag reporting rates suggest a decline in reporting rates in 2002 for all regions and for both single and double tagged fish. Amid rumours of impending reductions in future quotas and possible closures, some fishers expressed concerns and commented that they would not return tags if this would result in lower quotas in the future. This helps to explain why our reporting rate estimates decreased for 2002. Provided the high reward ($100) tags are all returned our estimates of reporting rates should be reasonable.

Our estimates of the fully selected exploitation rates in 3Ps_OF, and to a lesser extend 3Ps_WB, are much lower than those for other areas in spite of substantial landings. The estimates for these areas may be less reliable. The spatial extent of tagging experiments in 3Ps_OF has been limited, and the fishery has also been spatially concentrated. This may result in inaccurate estimates of exploitation rates. Also, many of the tagging experiments conducted in this region have involved tagging of cod caught in extremely deep water (>250 m) and tagging mortality at these depths may be much higher compared to the estimate of 0.13 for cod tagged in shallower inshore regions (Brattey and Cadigan, in press). Consequently, there may be fewer tagged cod available for recapture and exploitation rates of offshore cod tagged in deep water would be under-estimated. In addition, the estimates for 3Ps_OF are based on substantially fewer returns than inshore regions. Residual diagnostics also suggest that our preferred model does not explain the tag-recaptures from these two regions as well as from the other regions. If the estimates of exploitation rates in 3Ps_OF and 3Ps_WB are less reliable then the estimates for 3KL may be adversely affected, although we expect that this effect is small.

The weekly estimates of exploitation rates and biomass can be highly variable (Figs. 54-57), partly because of errors in reported tag capture dates and errors in reported fishing dates. The variability is well beyond realistic fluctuations in population size. We are investigating methods to smooth these variations and this is a useful area for future research.

References

[1] Brattey, J. and B. P. Healey. 2003. Exploitation rates and movements of Atlantic cod (*Gadus morhua*) in NAFO Divs. 3KL based on tagging experiments conducted during 1997-2002. *DFO Can. Science Advisory Secretariat Res. Doc.* 2003/032.

[2] Brattey, J., and Cadigan, N. G. 2004. Estimation of short term tagging mortality of Atlantic cod (*Gadus morhua*). *Fisheries Research* (accepted July 16, 2003).

[3] Cadigan, N. G., and J. Brattey. 2000. Estimation of cod (*Gadus morhua*) growth in NAFO Subdiv. 3Ps and Divs. 3KL in 1997-1999 from tagging experiments. *DFO Can. Science Advisory Secretariat Res. Doc.* 2000/074.

[4] Cadigan, N. G., and J. Brattey. 2001a. Estimation of the exploitation rates and migration rates for cod (*Gadus morhua*) in NAFO Divisions 3KL and Subdivision 3Ps during 1997-2000 from tagging experiments. ICES CM 2001/O:04. Available from: http://www.ices.dk/products/CMdocs/2001/O/O0401.pdf. Accessed November 2003.

[5] Cadigan, N. G., and J. Brattey. 2001b. A nonparametric Von Bertalanffy model for estimating growth curves of Atlantic cod. ICES CM 2001/O:18. Available from: http://www.ices.dk/products/CMdocs/2001/O/O1801.pdf. Accessed November 2003.

[6] Cadigan, N. G. and Brattey, J. 2002. Updated estimates of exploitation rates and biomass for cod (*Gadus morhua*) in NAFO Divisions 3KL and Subdivision 3Ps during 1997-2000 from tagging experiments in these years. *DFO Can. Science Advisory Secretariat Res. Doc.* 2002/021.

[7] Cadigan, N. G. and Brattey, J. 2004. Semi-parametric estimation of tag loss and reporting rates for tagging experiments using exact time-at-liberty data. *Biometrics*, **59**, 869-876.

[8] Healey, B. P., and N. G. Cadigan. 2001. Smoothing length frequency data via kernel density estimation. *DFO Can. Science Advisory Secretariat Res. Doc.* 2001/071.

[9] Kirkwood, G. P. (1981). Generalized models for the estimation of the rates of tag shedding by southern bluefin tuna (*Thunnus maccoyii*). *Journal du Conseil* **39**, 256-260.

5 Appendix: Figures

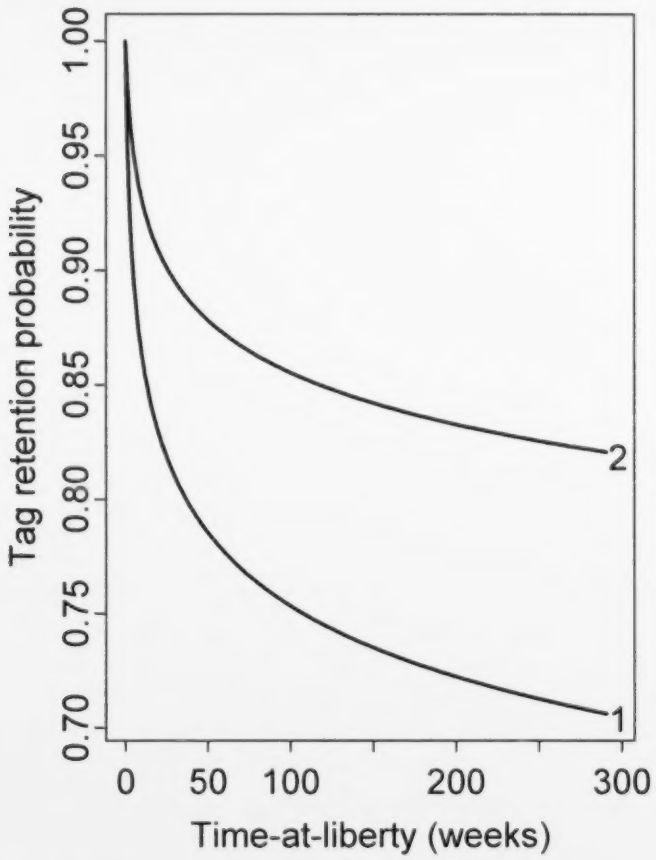

Figure 1: Estimates of $\Phi_1(t)$ and $\Phi_2(t)$ using Kirkwood's parametric model. The right-hand numbers indicate the tag position on the fish: 1 - front, 2 - back (see text for details).

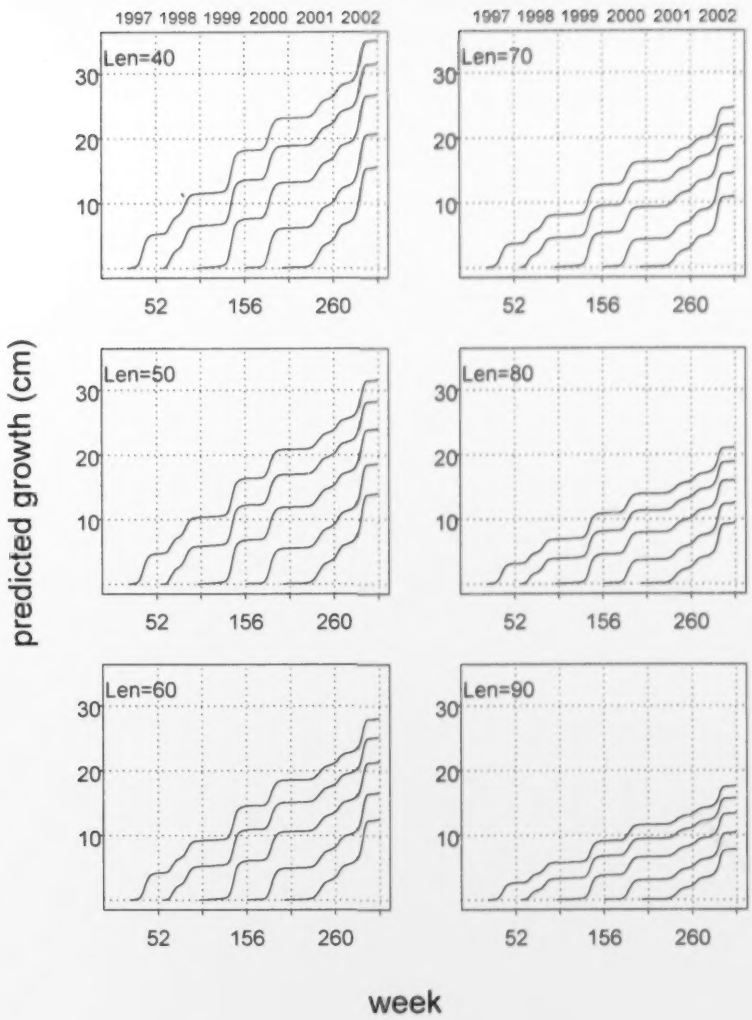

Figure 2: Estimated Von Bertalanffy growth curves for a range of release length classes and release dates. For example, a 40 cm fish released in week 20 is estimated to grow 34 cm by week 312 (i.e. $5\frac{1}{2}$ years at liberty).

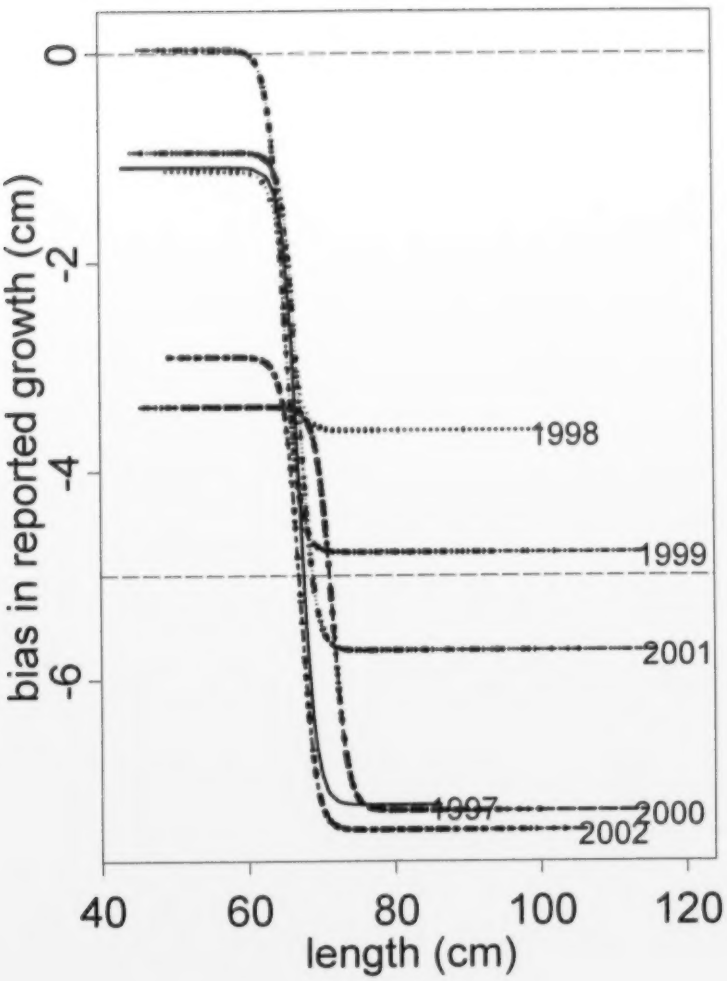

Figure 3: Estimated annual bias functions.

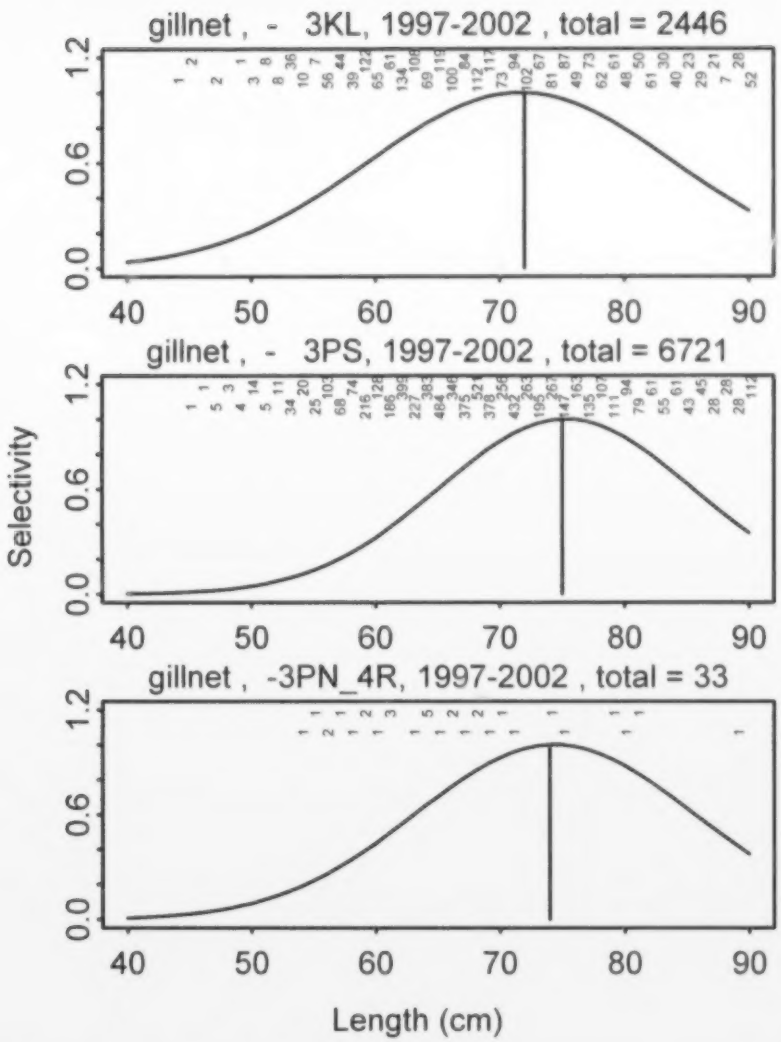

Figure 4: Estimated relative selectivity of gillnets. The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

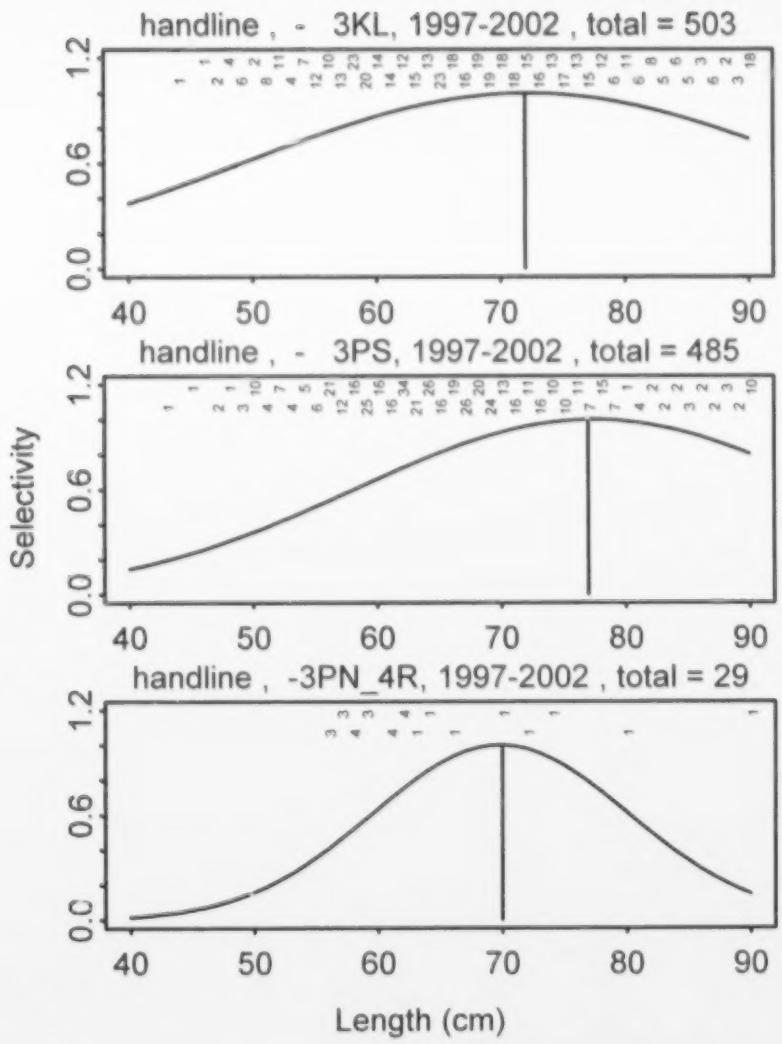

Figure 5: Estimated relative selectivity of handlines. The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

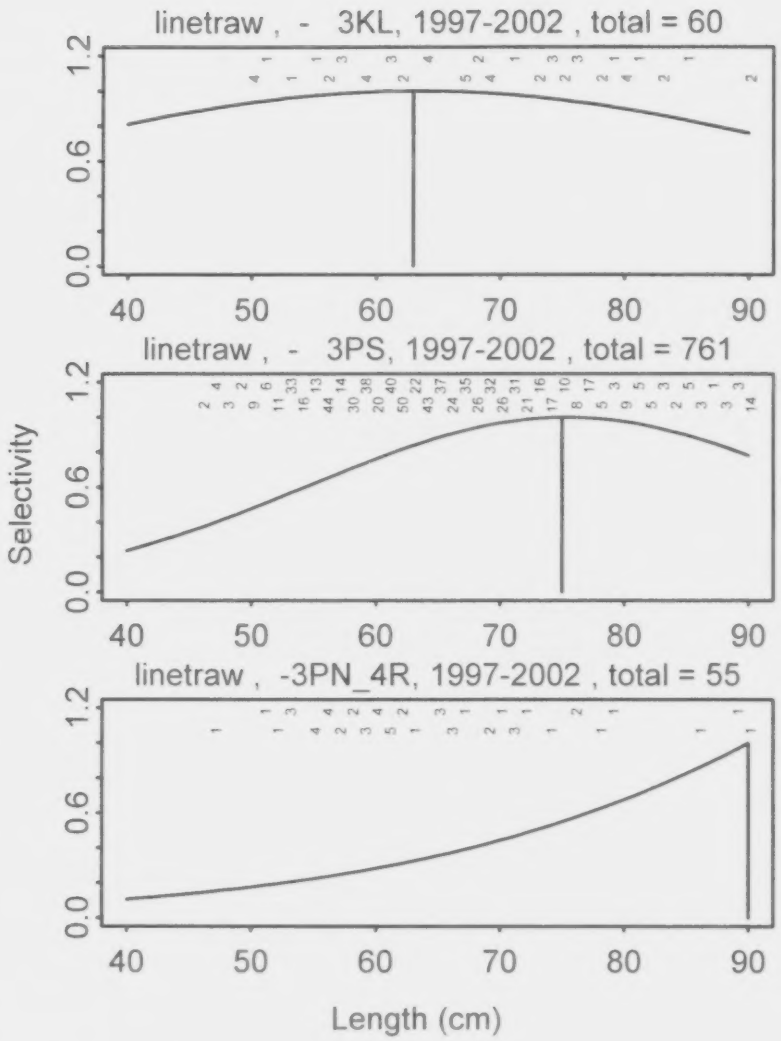

Figure 6: Estimated relative selectivity of linetrawls. The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

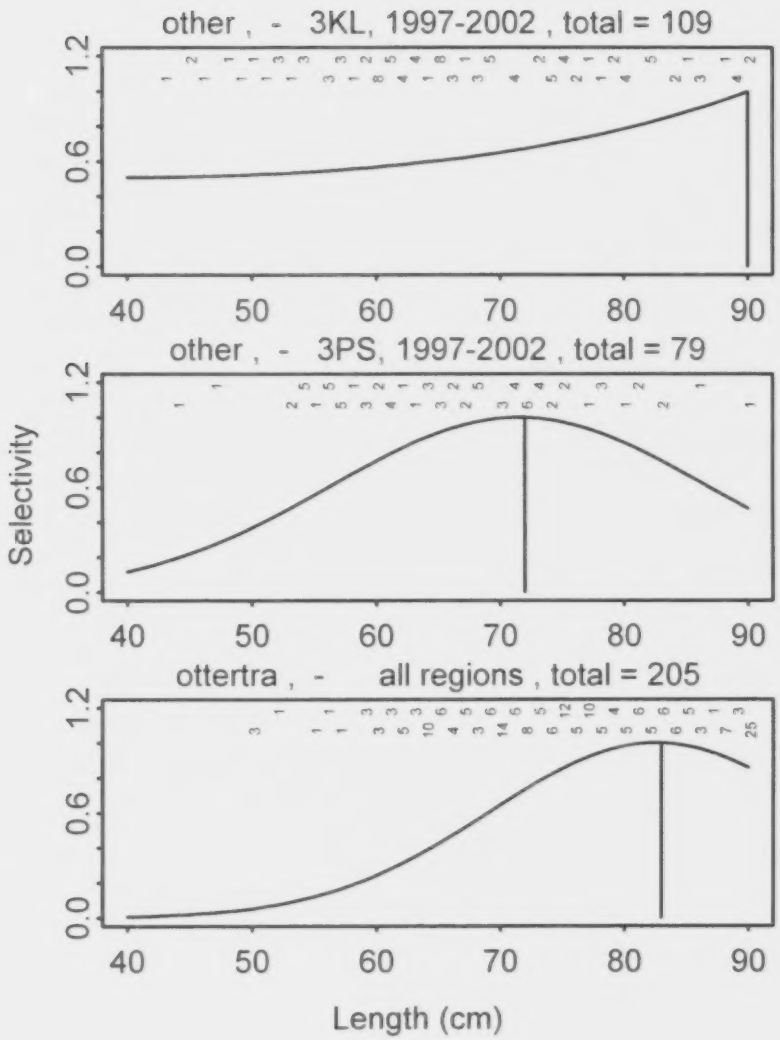

Figure 7: Estimated relative selectivity of ottertrawls and gears classified as "other". The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

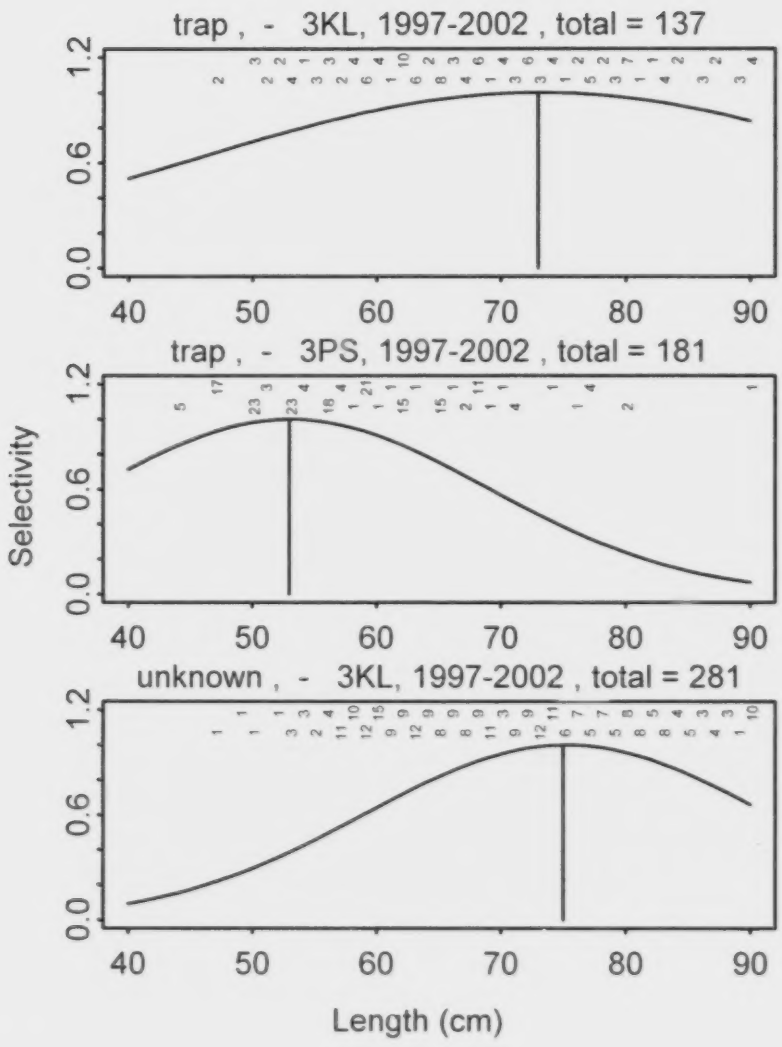

Figure 8: Estimated relative selectivity of cod traps and gears not reported (i.e. unknown). The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

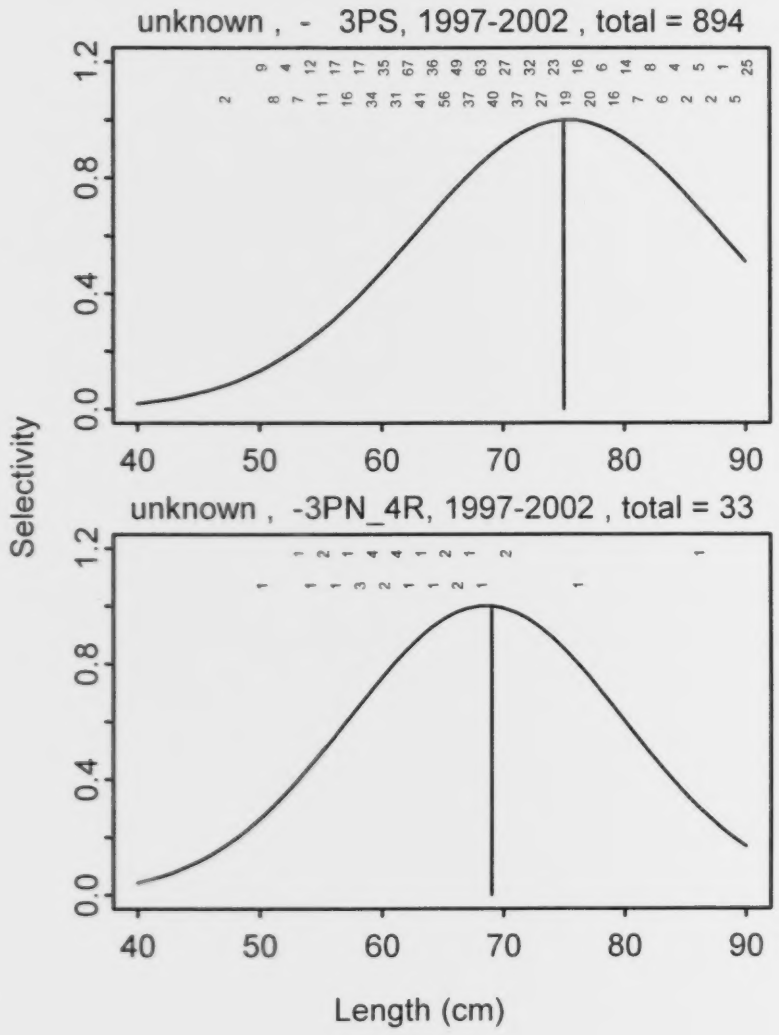

Figure 9: Estimated relative selectivity of gears not reported (i.e. unknown). The numbers of tag-returns per 1 cm length class are shown before the top of each panel, and the total number for all lengths is shown at the top. The vertical line marks the fully selected length.

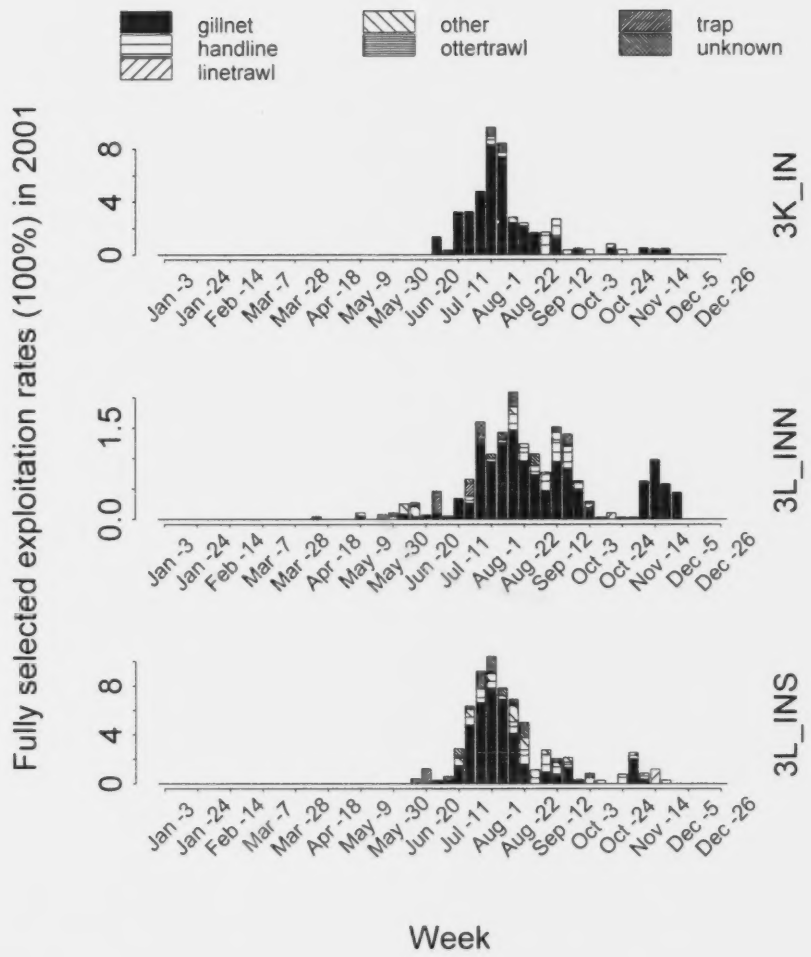

Figure 10: Weekly estimates of the fully selected exploitation rates for each gear type used in the **3KL** regions in 2001. Each panel represents a region, which is labelled on the right-hand side. The bar-blocking shows the weekly estimates for each gear type (legend at top). The calender dates of the week mid-points are shown along the x-axis in each panel. **Note:** the height of the y-axis is different in each panel.

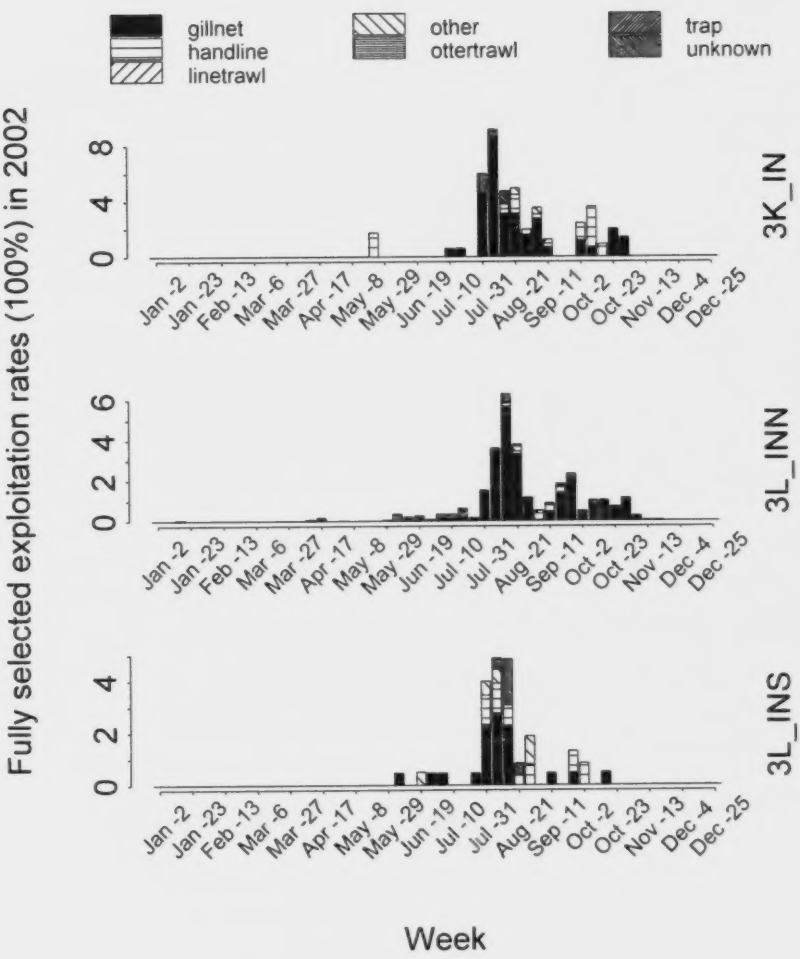

Figure 11: Weekly estimates of the fully selected exploitation rates for each gear type used in the **3KL** regions in 2002. Each panel represents a region, which is labelled on the right-hand side. The bar-blocking shows the weekly estimates for each gear type (legend at top). The calender dates of the week mid-points are shown along the x-axis in each panel. **Note:** the height of the y-axis is different in each panel.

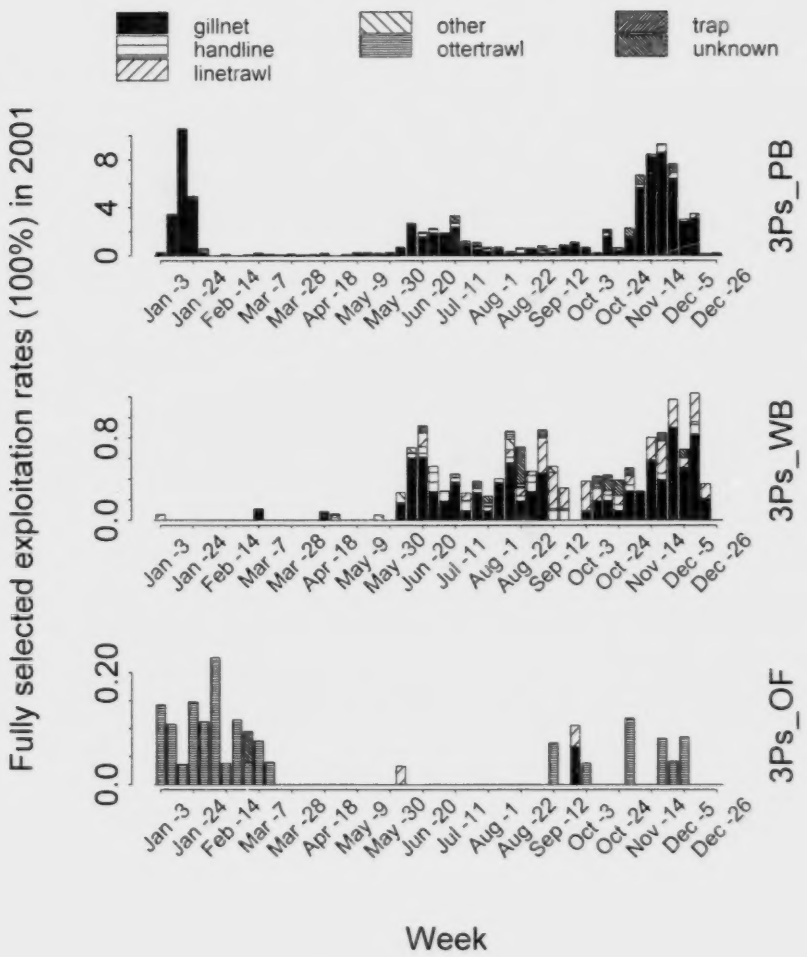

Figure 12: Weekly estimates of the fully selected exploitation rates for each gear type used in the **3Ps** regions in 2001. Each panel represents a region, which is labelled on the right-hand side. The bar-blocking shows the weekly estimates for each gear type (legend at top). The calender dates of the week mid-points are shown along the x-axis in each panel. **Note:** the height of the y-axis is different in each panel.

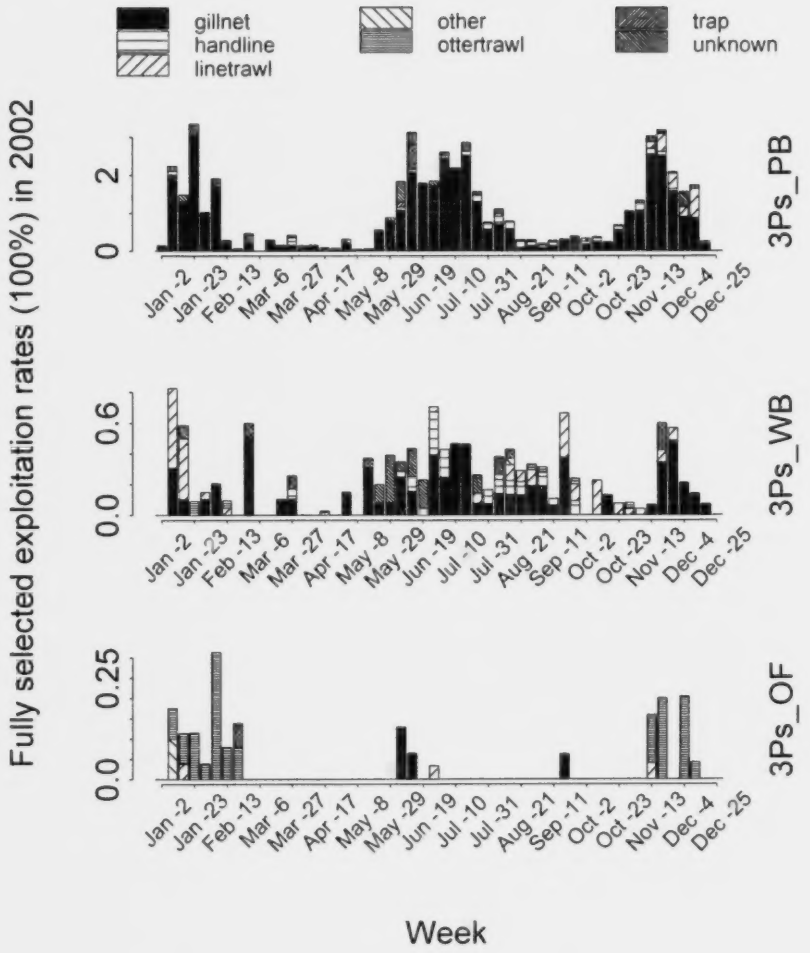

Figure 13: Weekly estimates of the fully selected exploitation rates for each gear type used in the **3Ps** regions in 2002. Each panel represents a region, which is labelled on the right-hand side. The bar-blocking shows the weekly estimates for each gear type (legend at top). The calender dates of the week mid-points are shown along the x-axis in each panel. **Note:** the height of the y-axis is different in each panel.

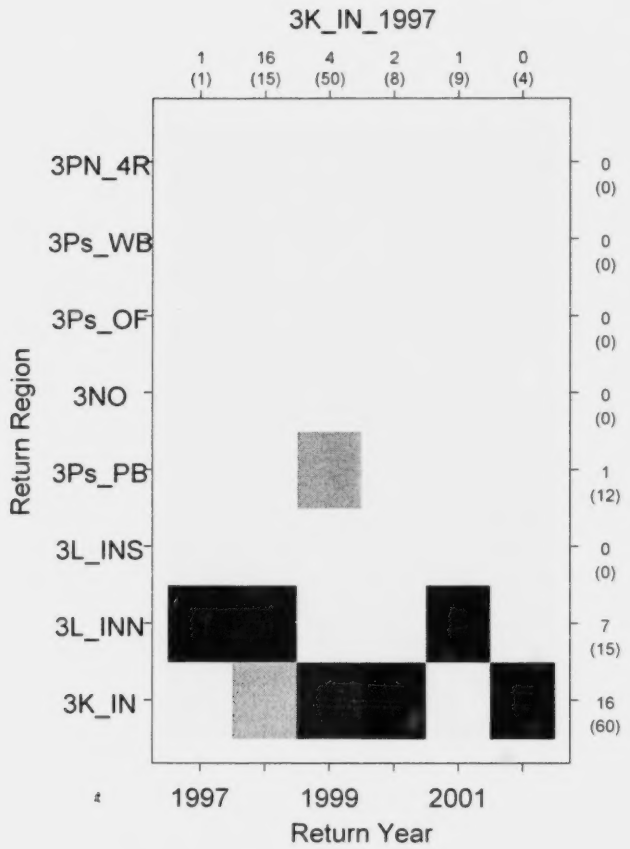

Figure 14: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

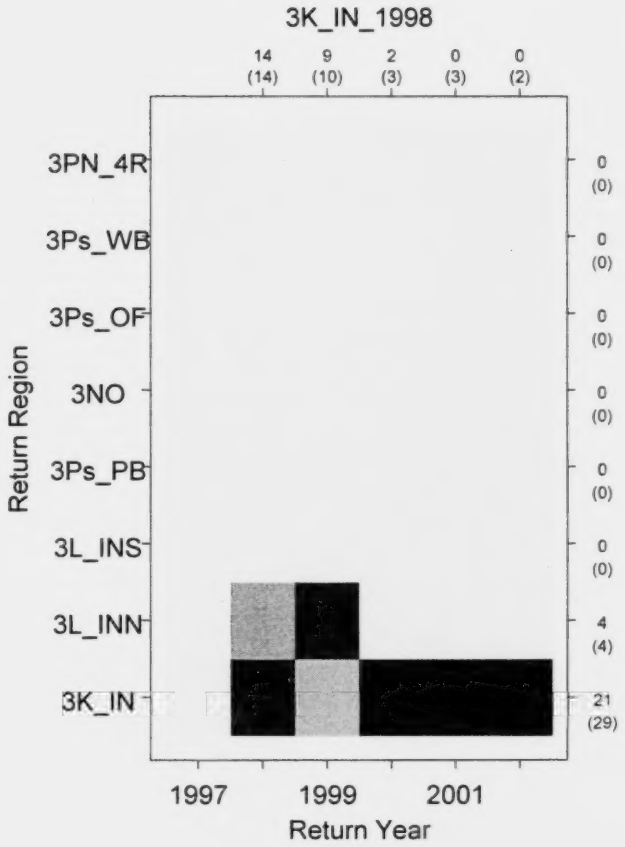

Figure 15: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

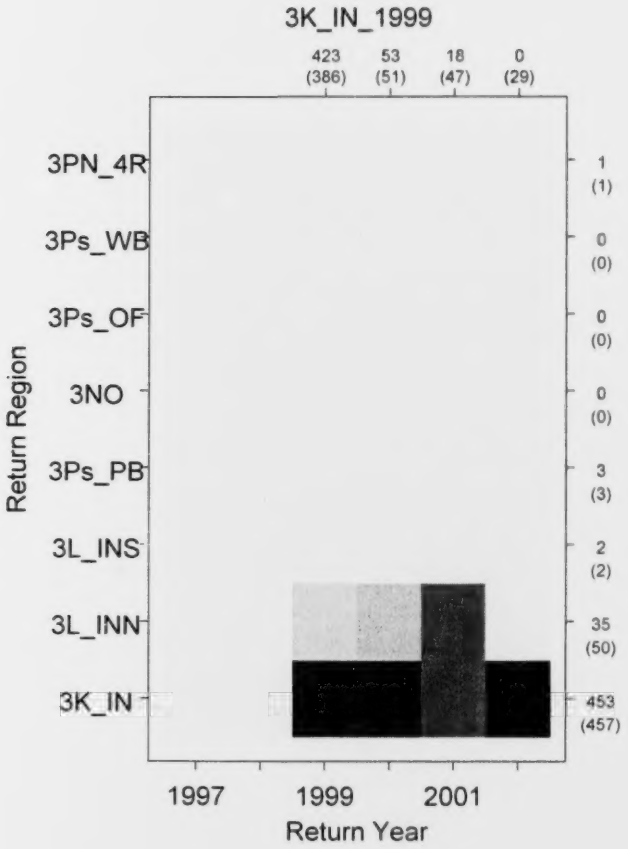

Figure 16: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

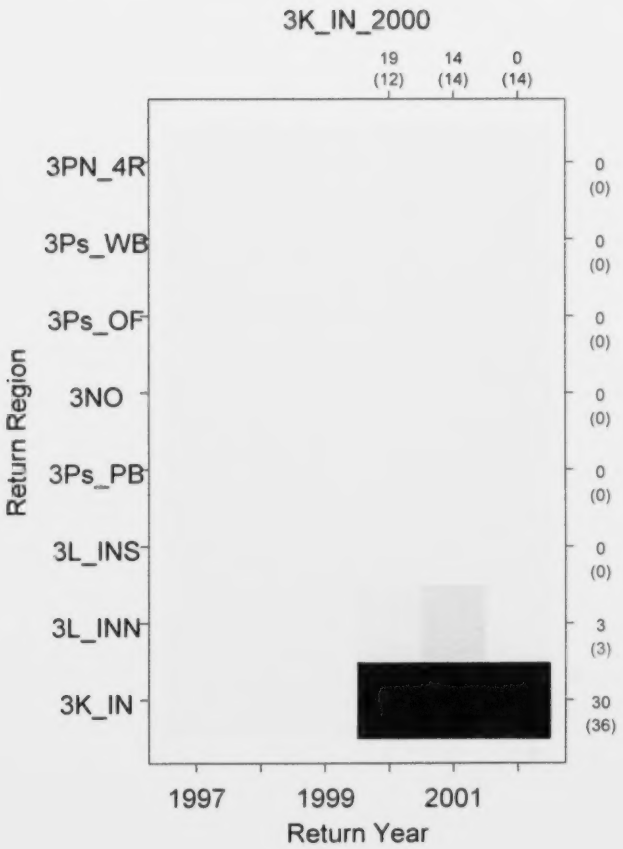

Figure 17: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

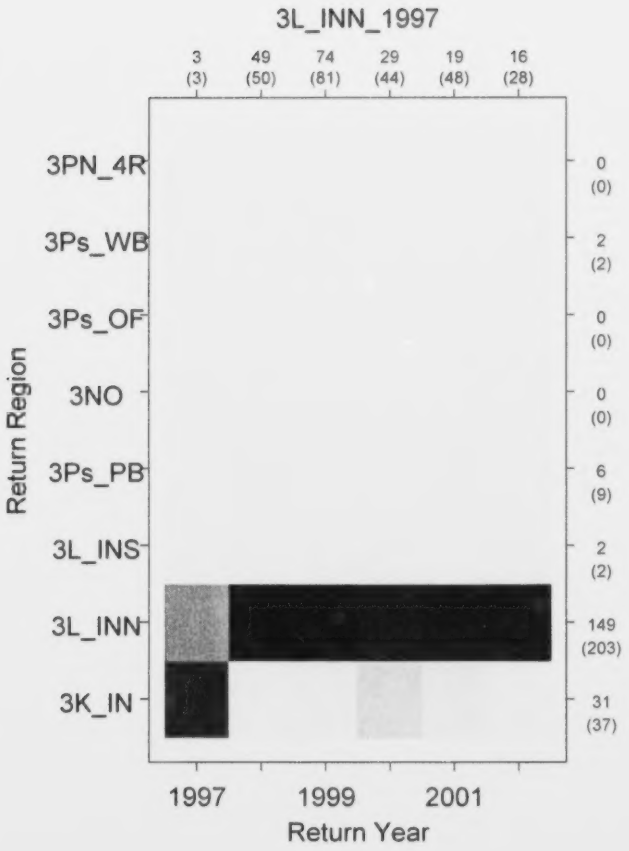

Figure 18: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

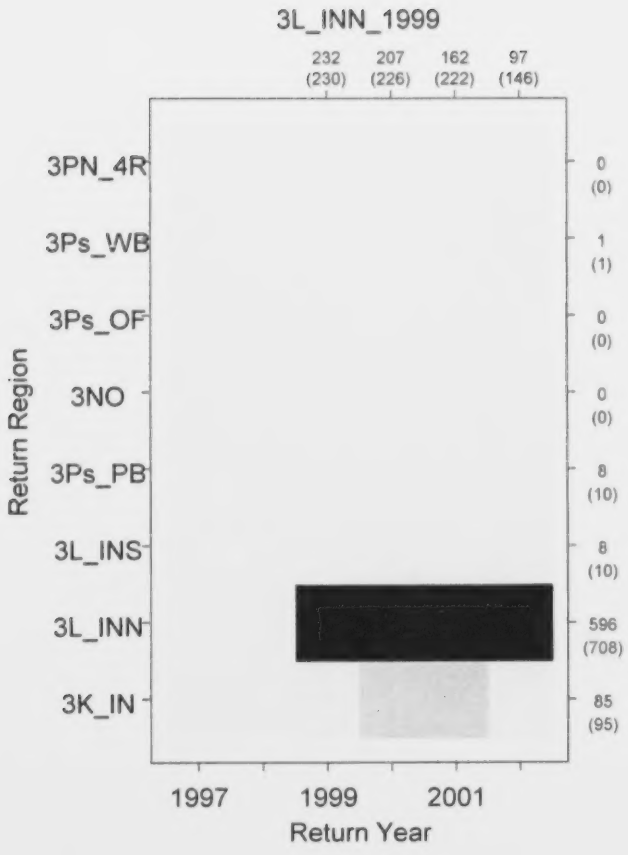

Figure 19: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

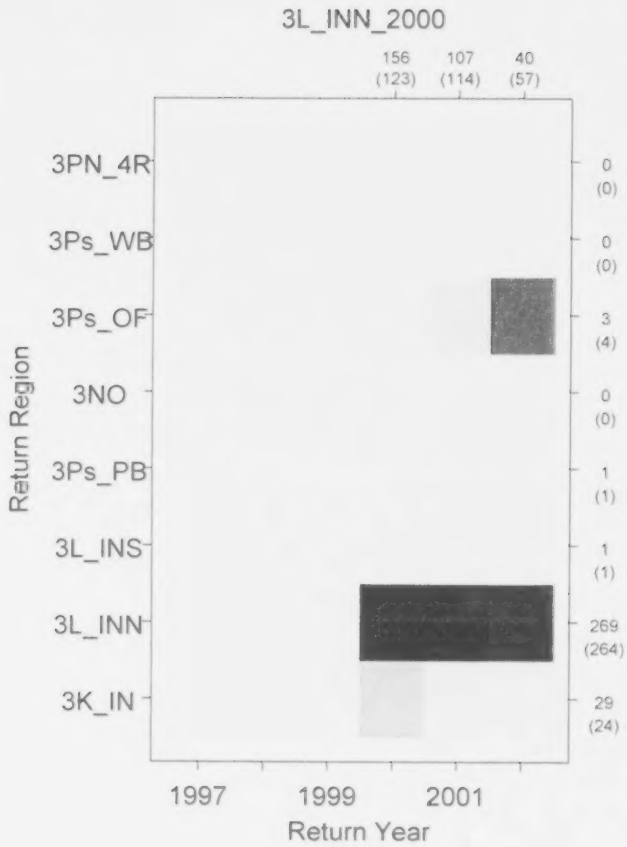

Figure 20: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

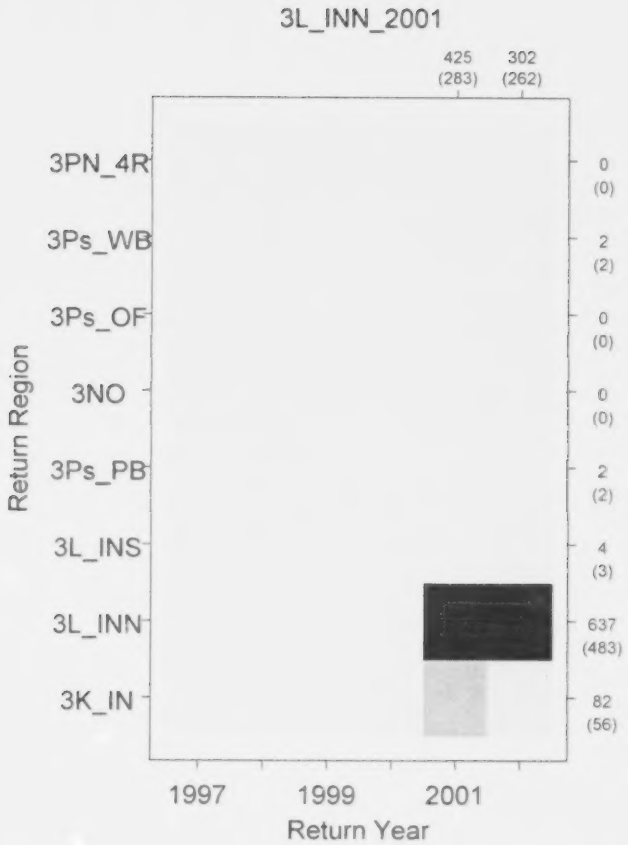

Figure 21: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

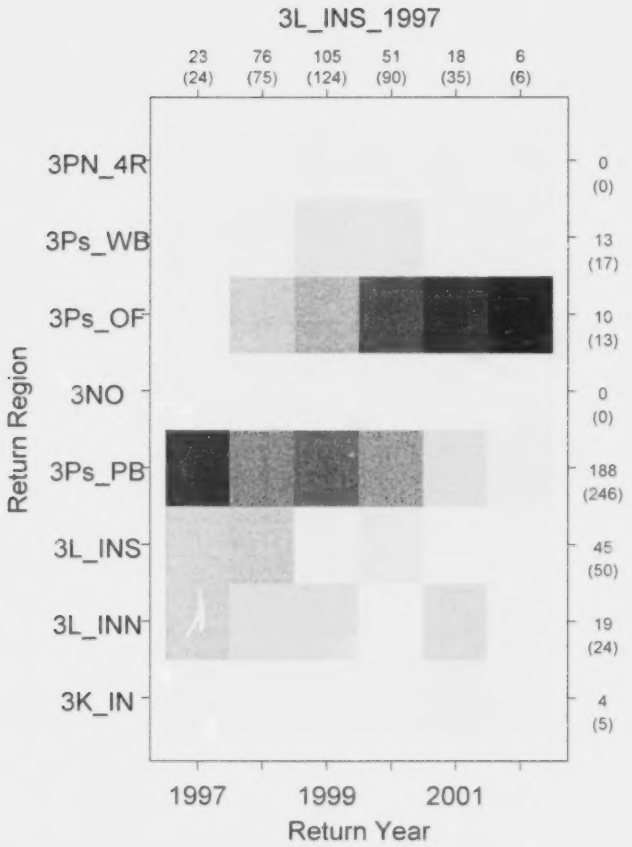

Figure 22: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

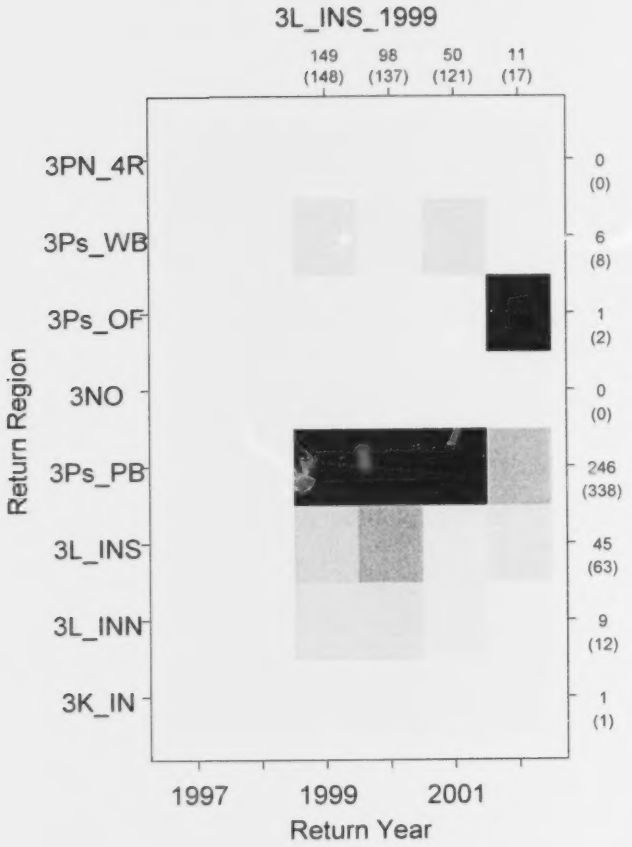

Figure 23: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The rclease region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

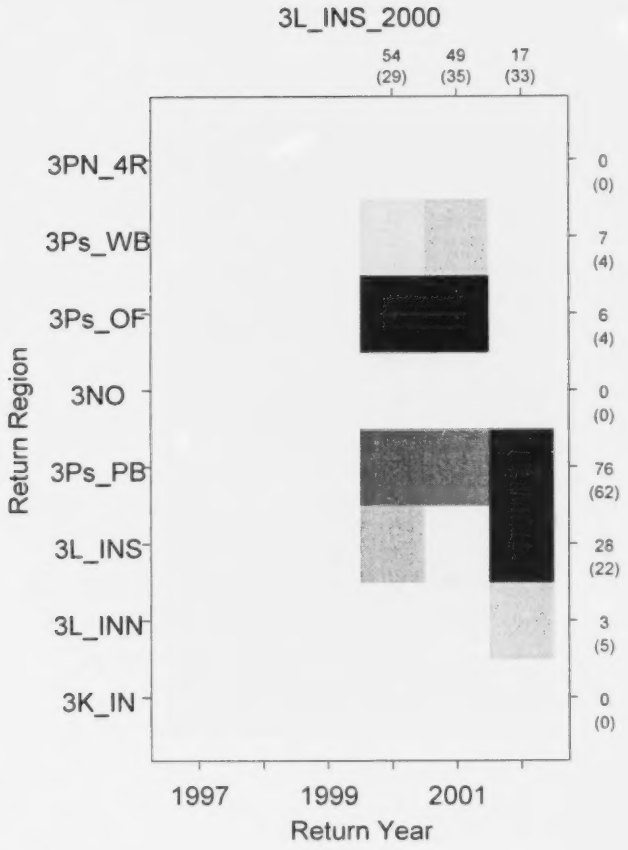

Figure 24: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

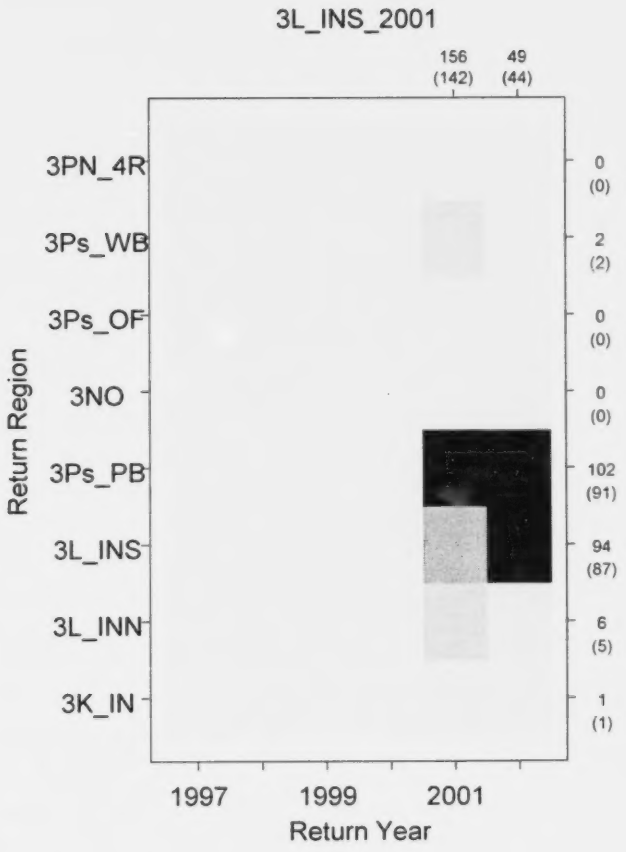

Figure 25: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

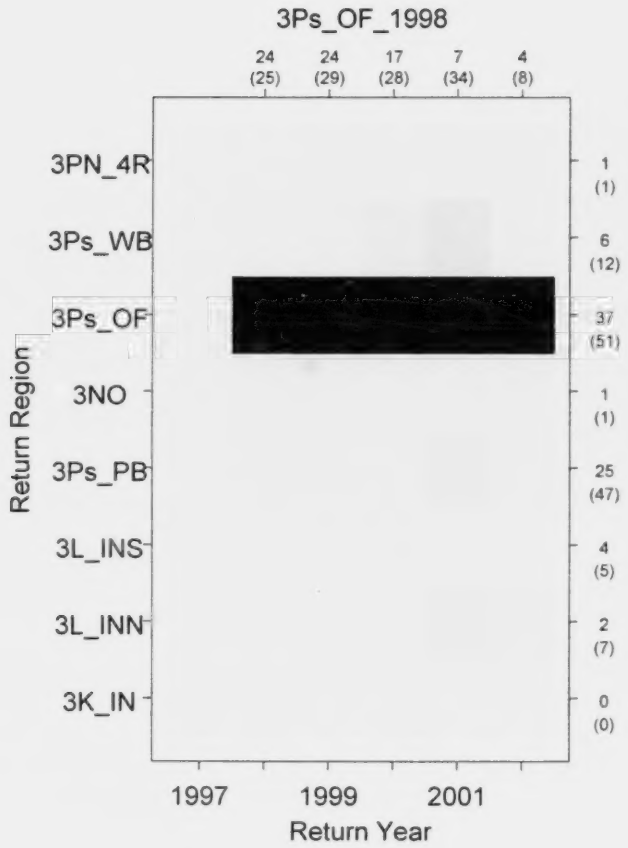

Figure 26: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

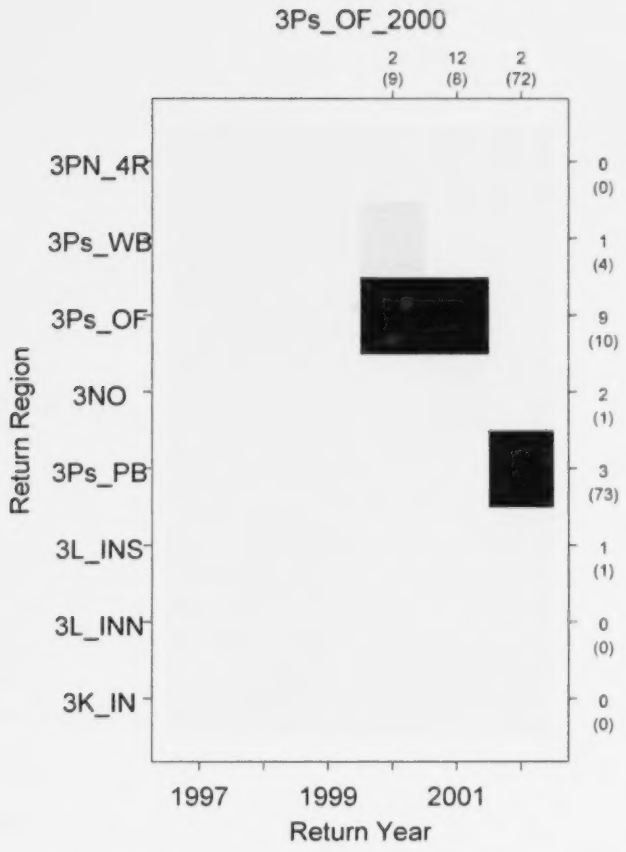

Figure 27: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

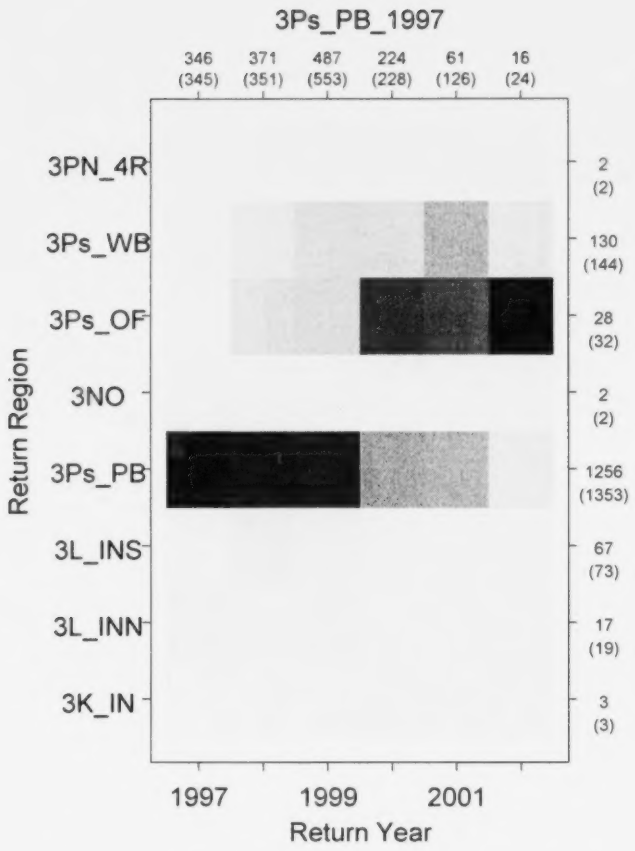

Figure 28: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

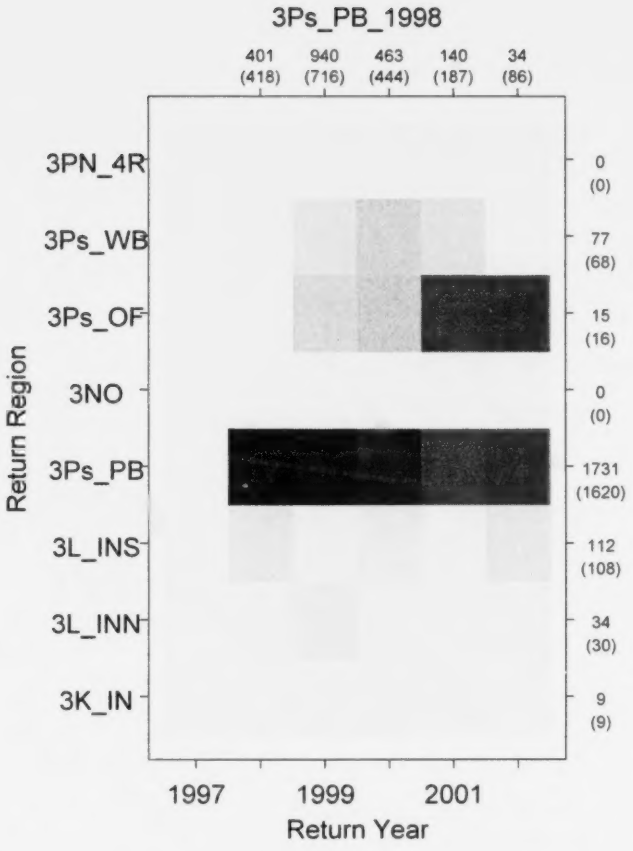

Figure 29: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

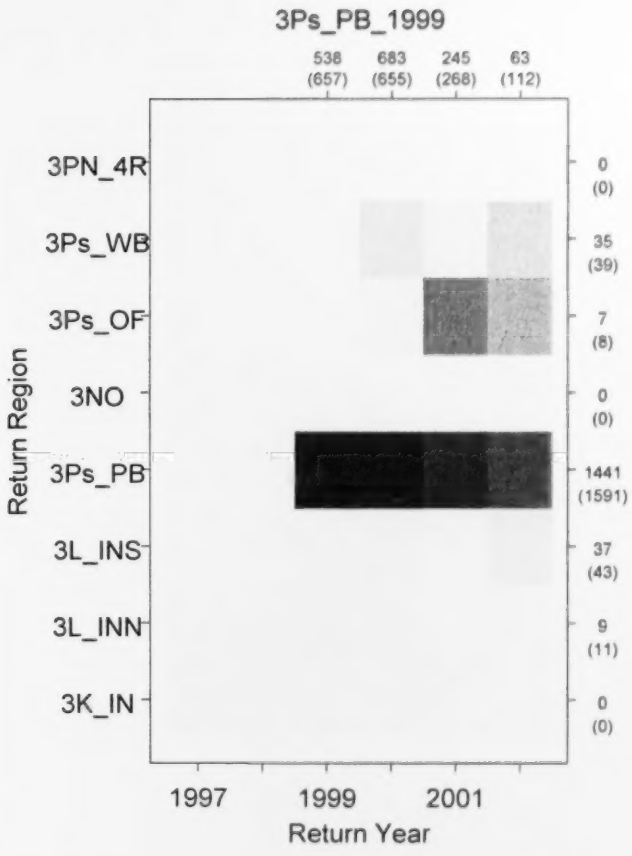

Figure 30: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

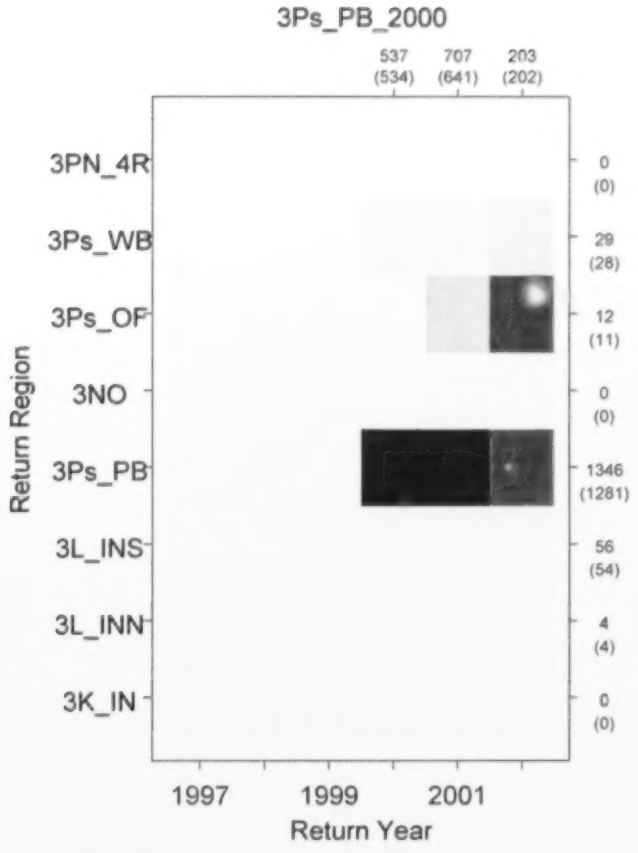

Figure 31: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

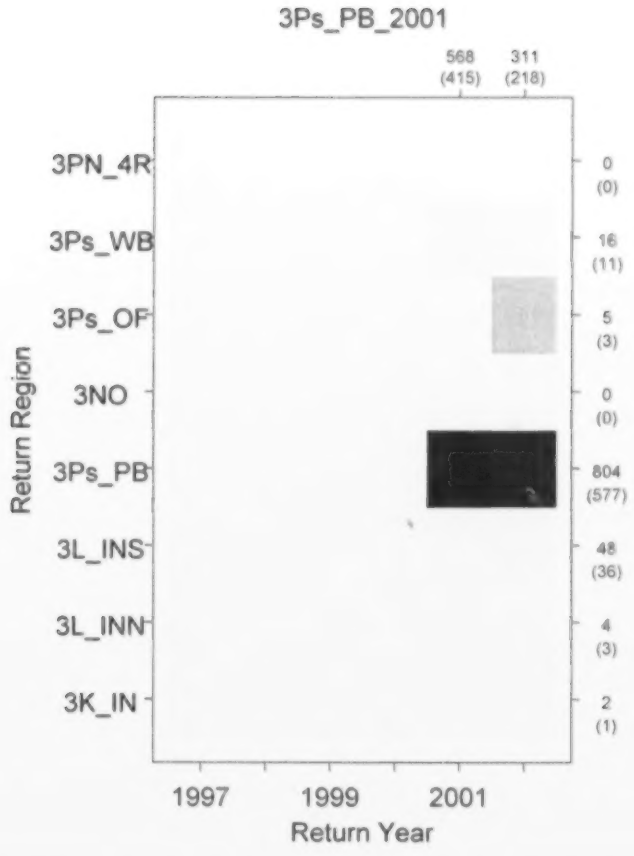

Figure 32: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

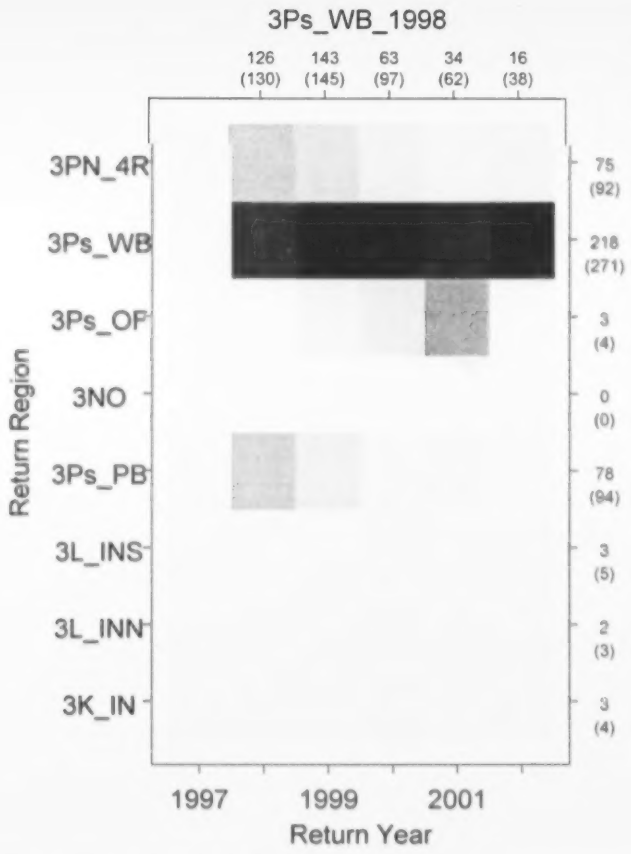

Figure 33: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

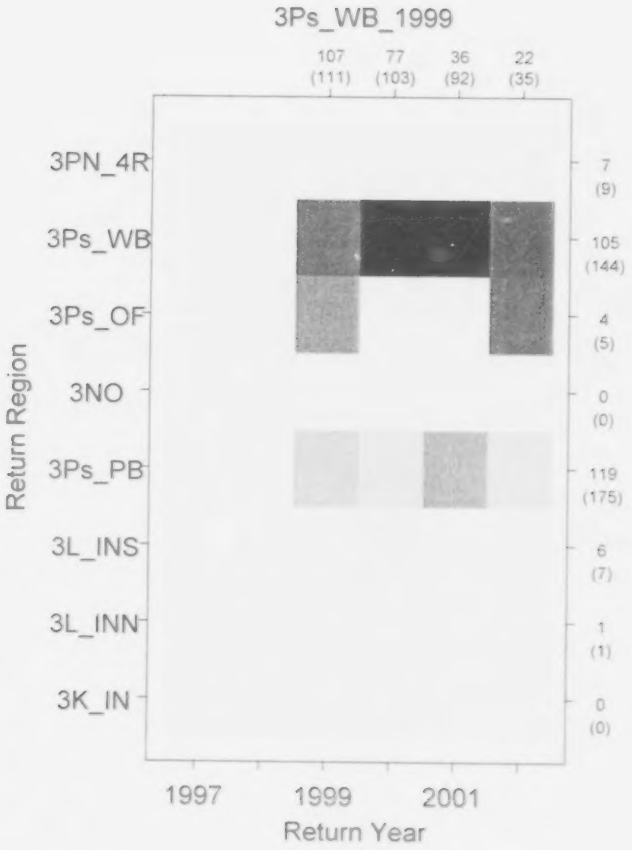

Figure 34: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

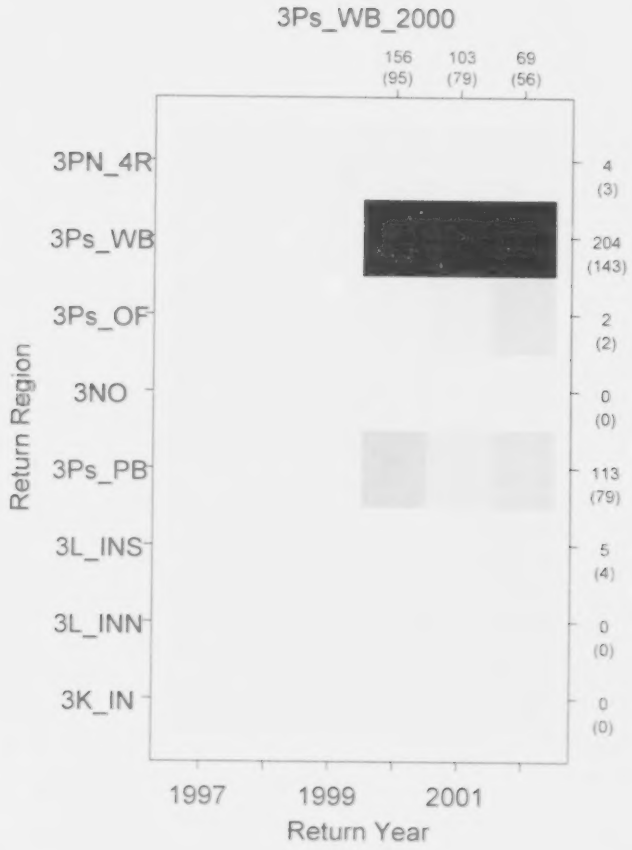

Figure 35: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

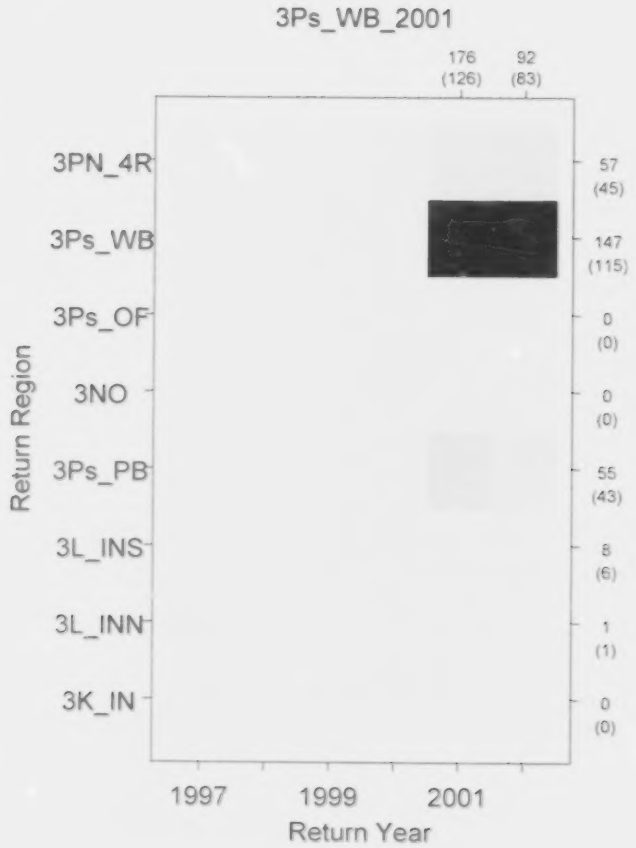

Figure 36: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

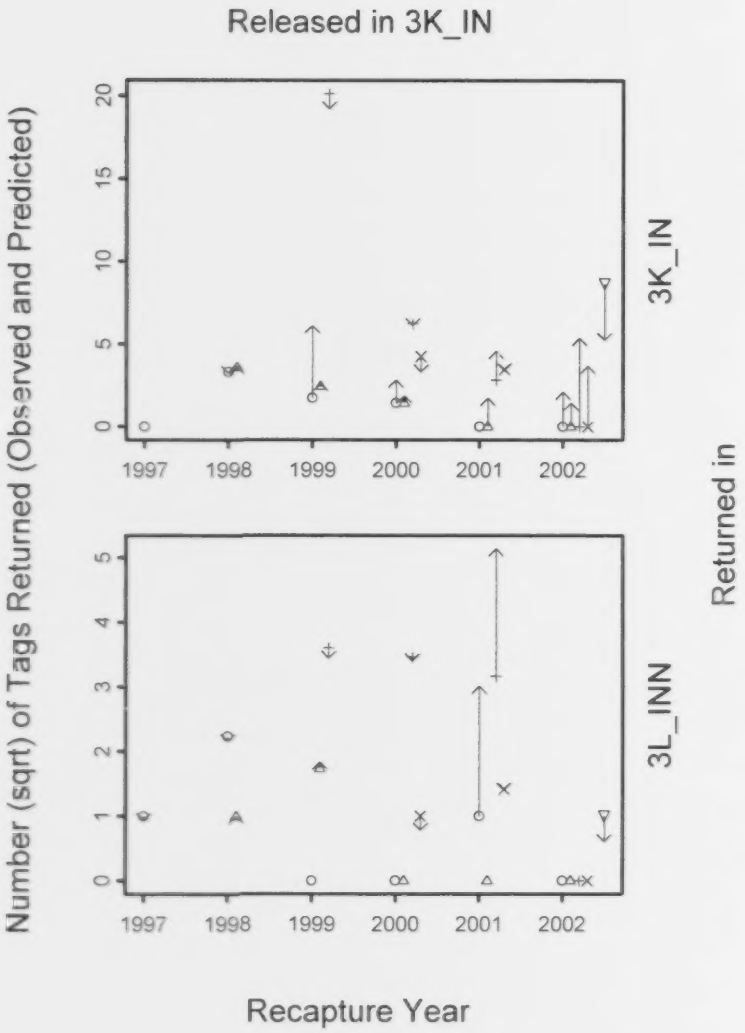

Figure 37: Annual total observed and predicted tag-recaptures for each release year in 3K_IN. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

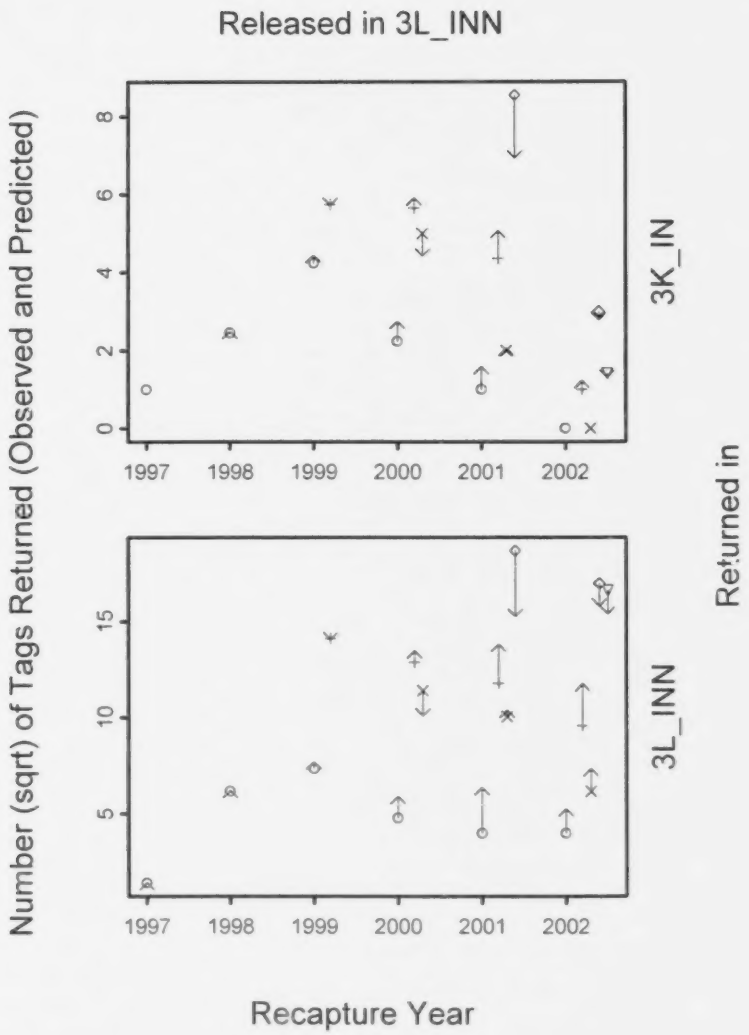

Figure 38: Annual total observed and predicted tag-recaptures for each release year in 3L_INN. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

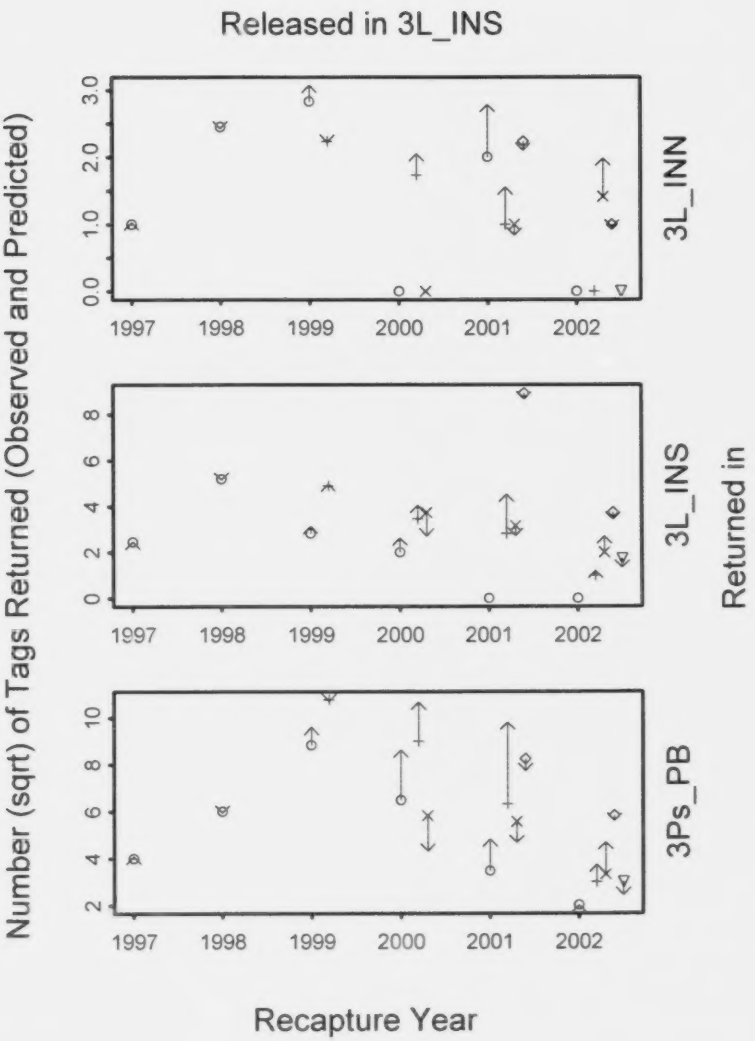

Figure 39: Annual total observed and predicted tag-recaptures for each release year in 3L_INS. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

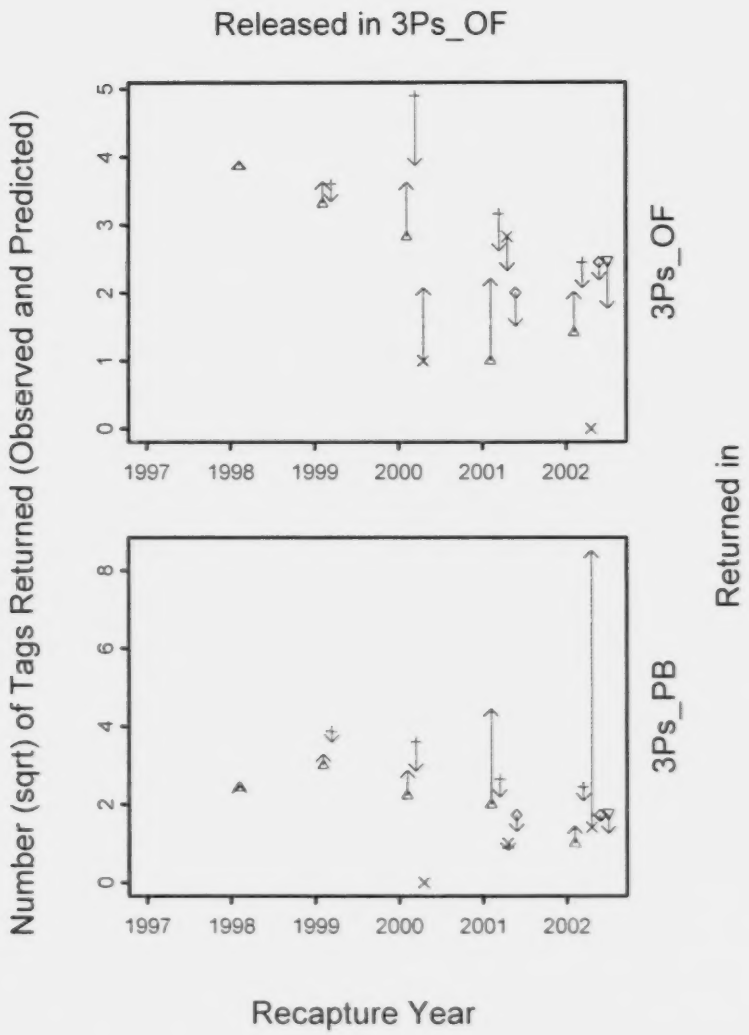

Figure 40: Annual total observed and predicted tag-recaptures for each release year in 3Ps_OF. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

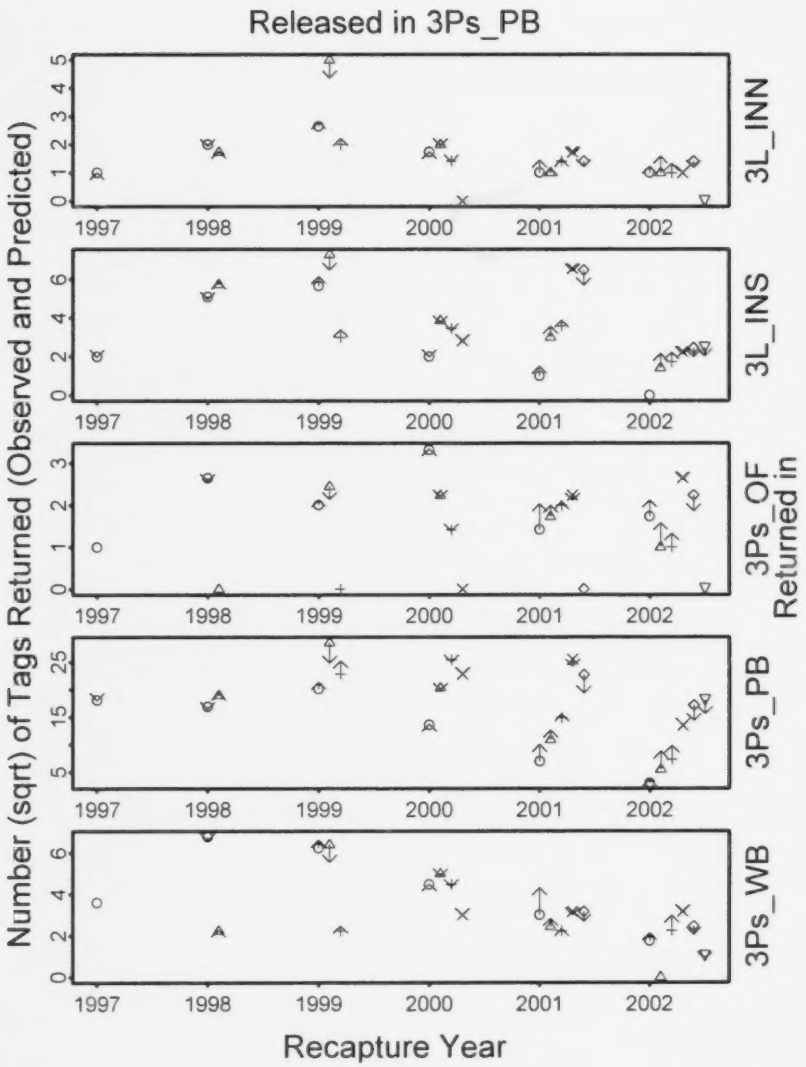

Figure 41: Annual total observed and predicted tag-recaptures for each release year in 3Ps_PB. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

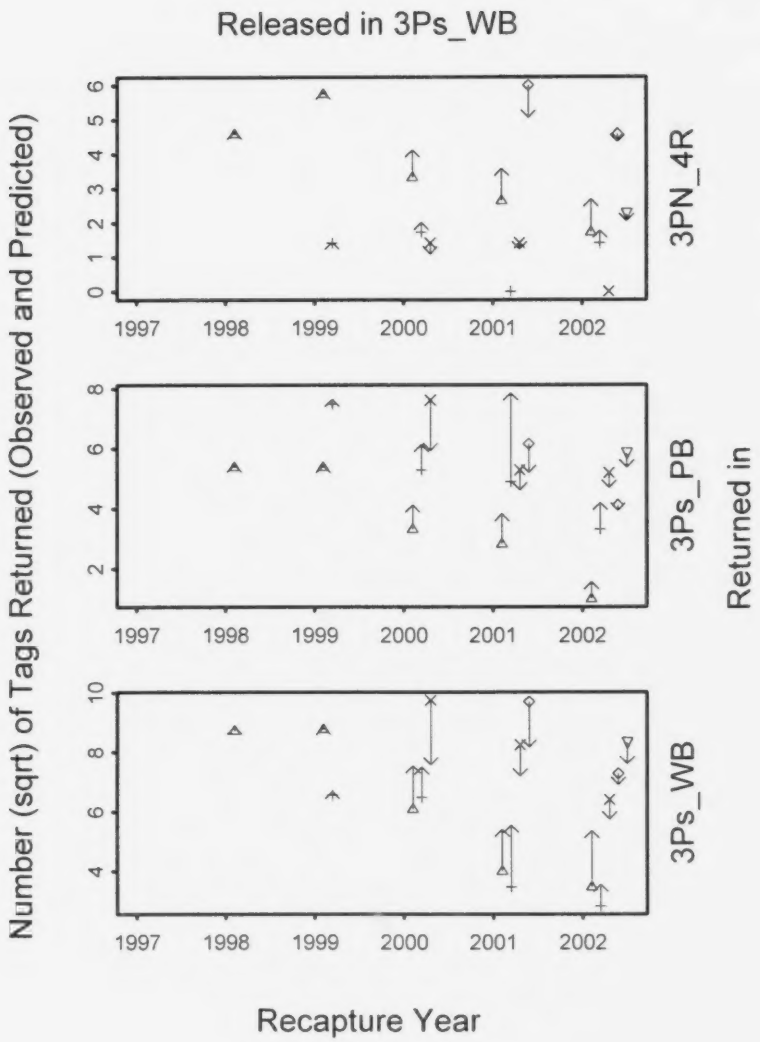

Figure 42: Annual total observed and predicted tag-recaptures for each release year in 3Ps_WB. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

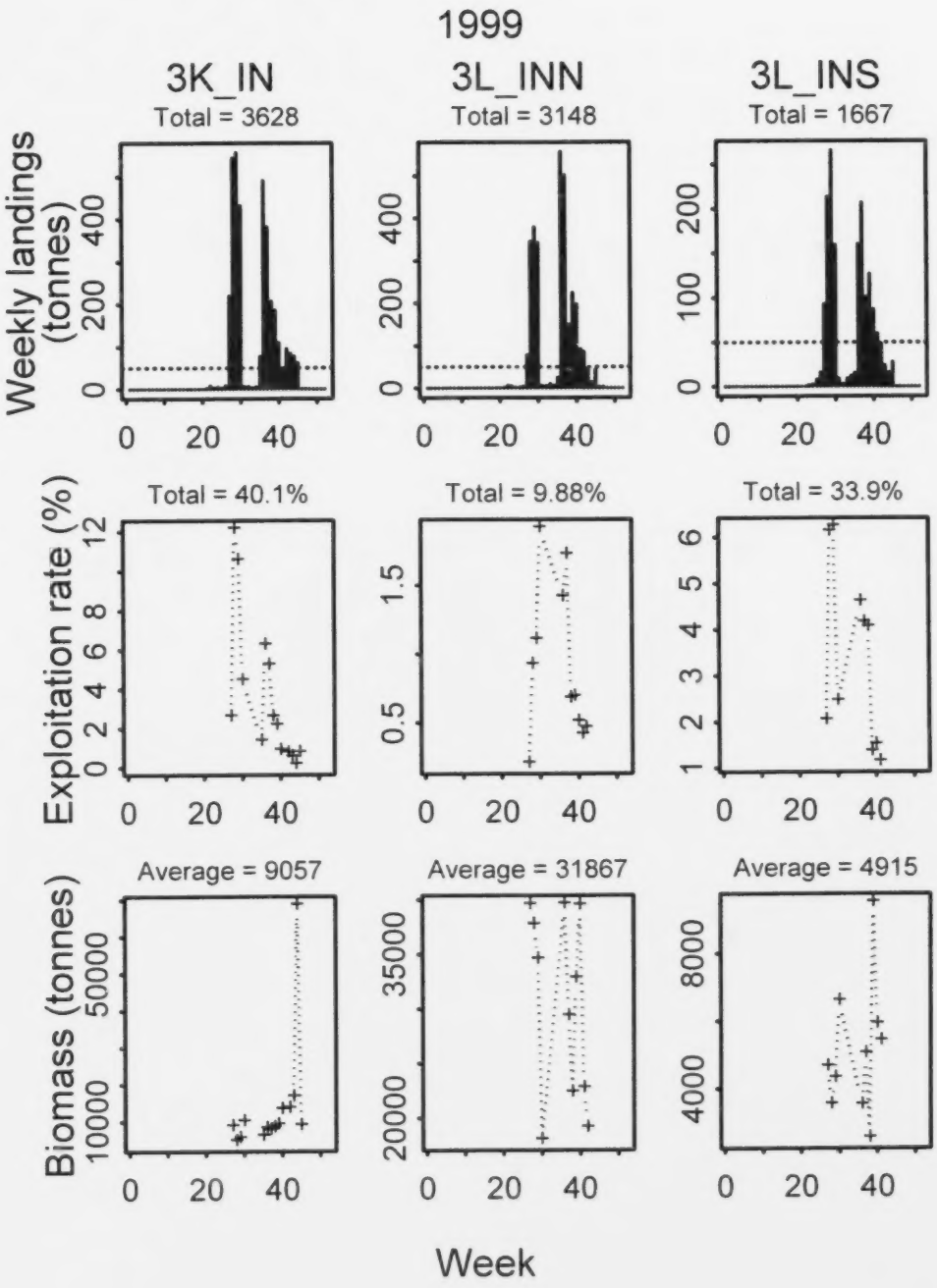

Figure 43: Estimates of total exploitation rates and biomass of cod in 3KL during 1999 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

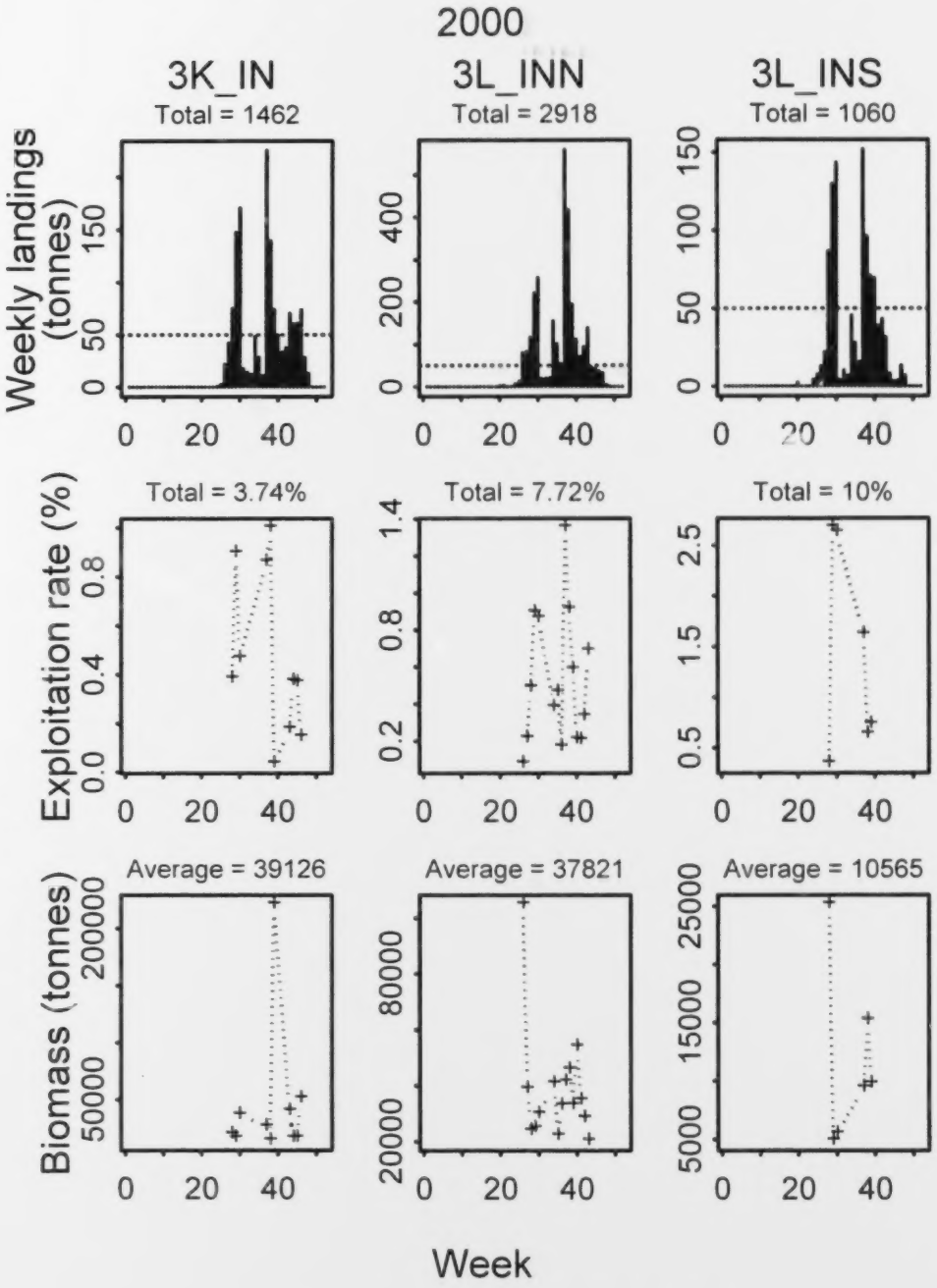

Figure 44: Estimates of total exploitation rates and biomass of cod in 3KL during 2000 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

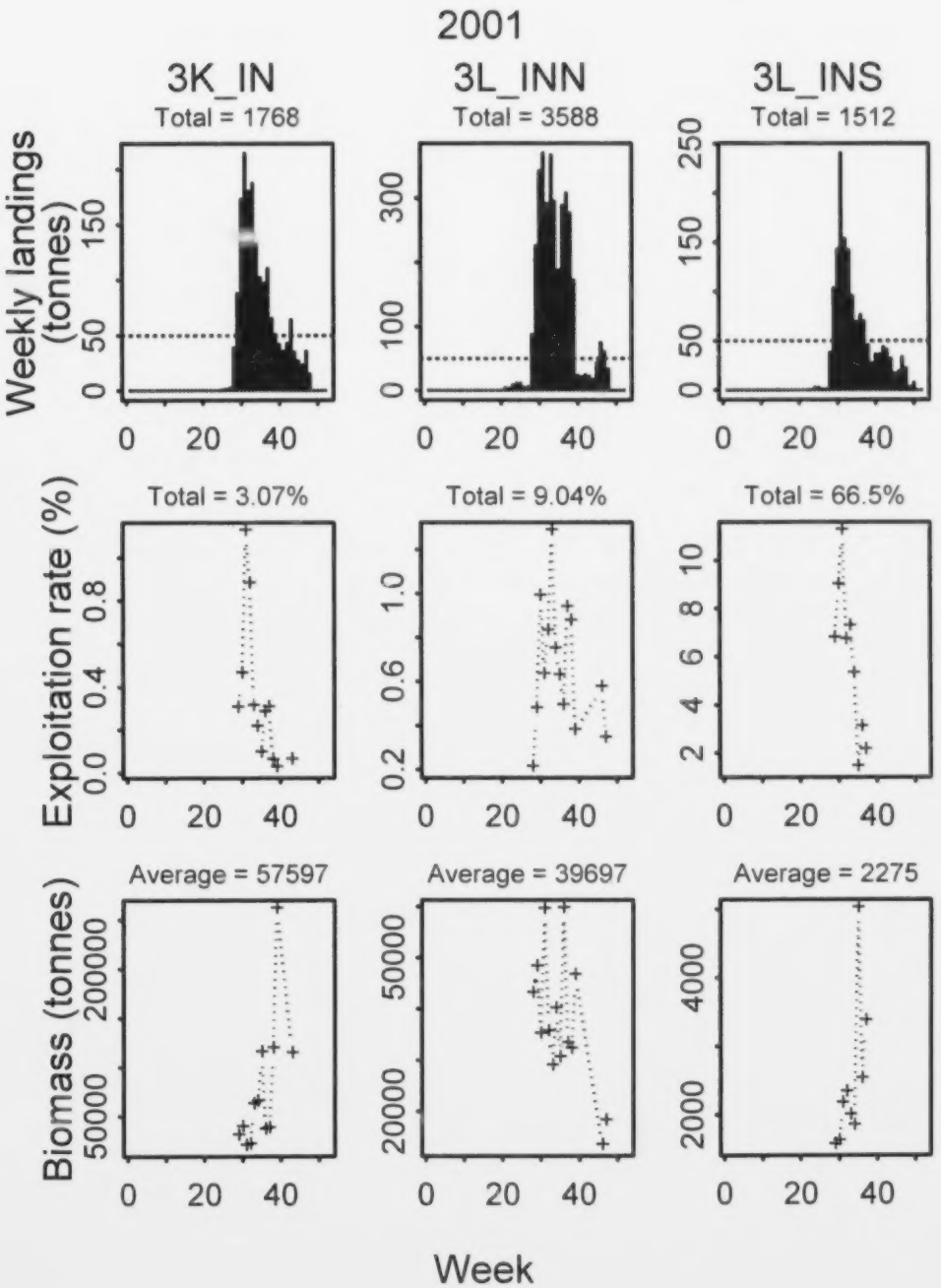

Figure 45: Estimates of total exploitation rates and biomass of cod in 3KL during 2001 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

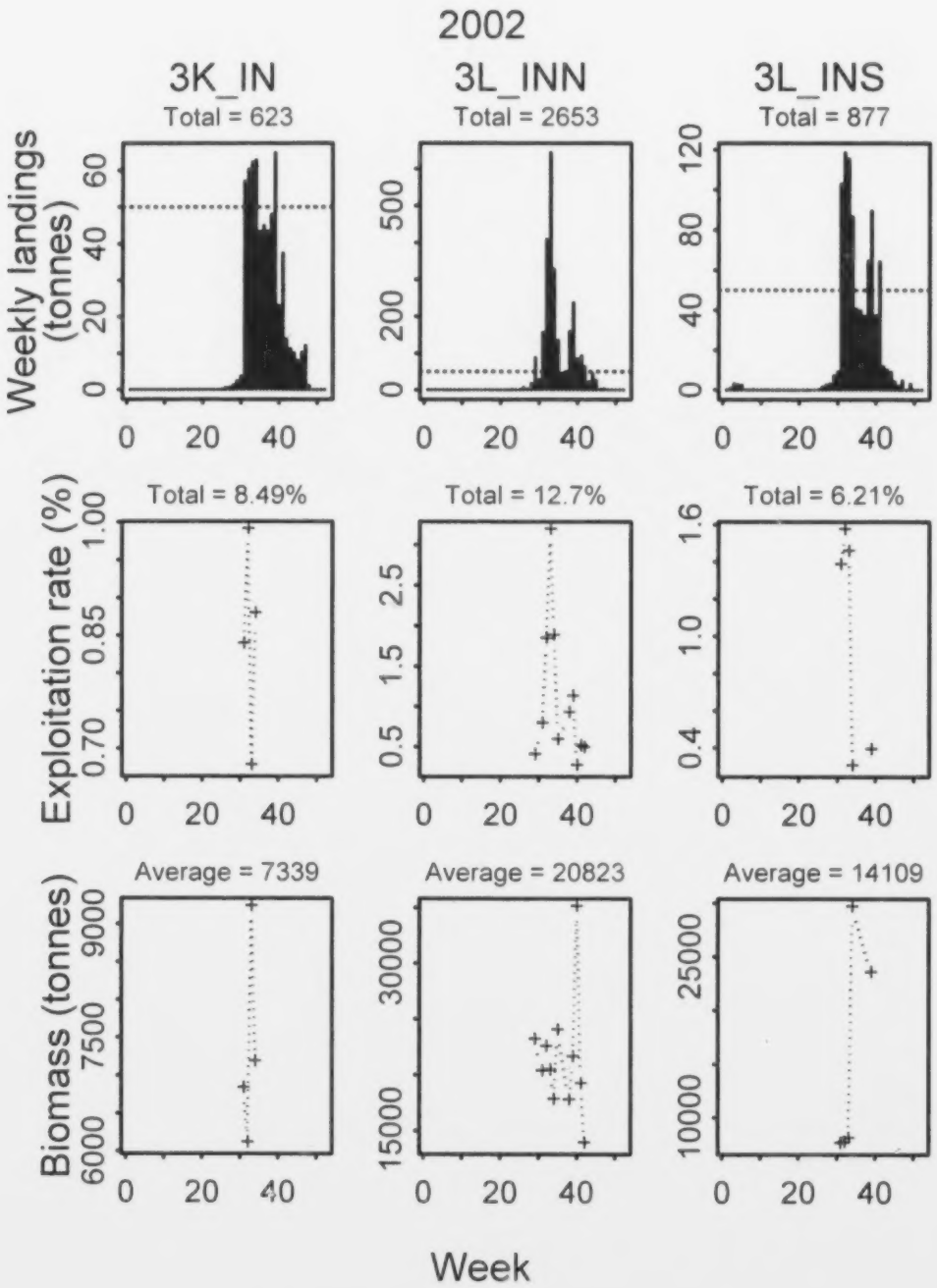

Figure 46: Estimates of total exploitation rates and biomass of cod in 3KL during 2002 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

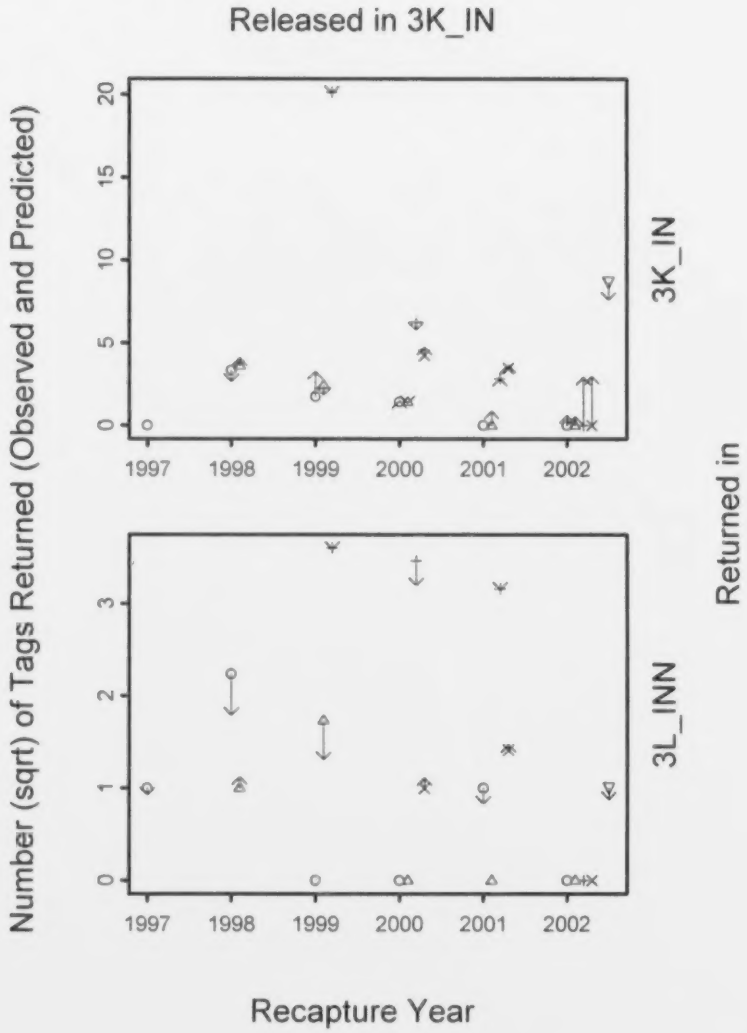

Figure 47: Annual total observed and predicted tag-recaptures for each release year in 3K_IN. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\bigtriangledown \equiv 2002$.

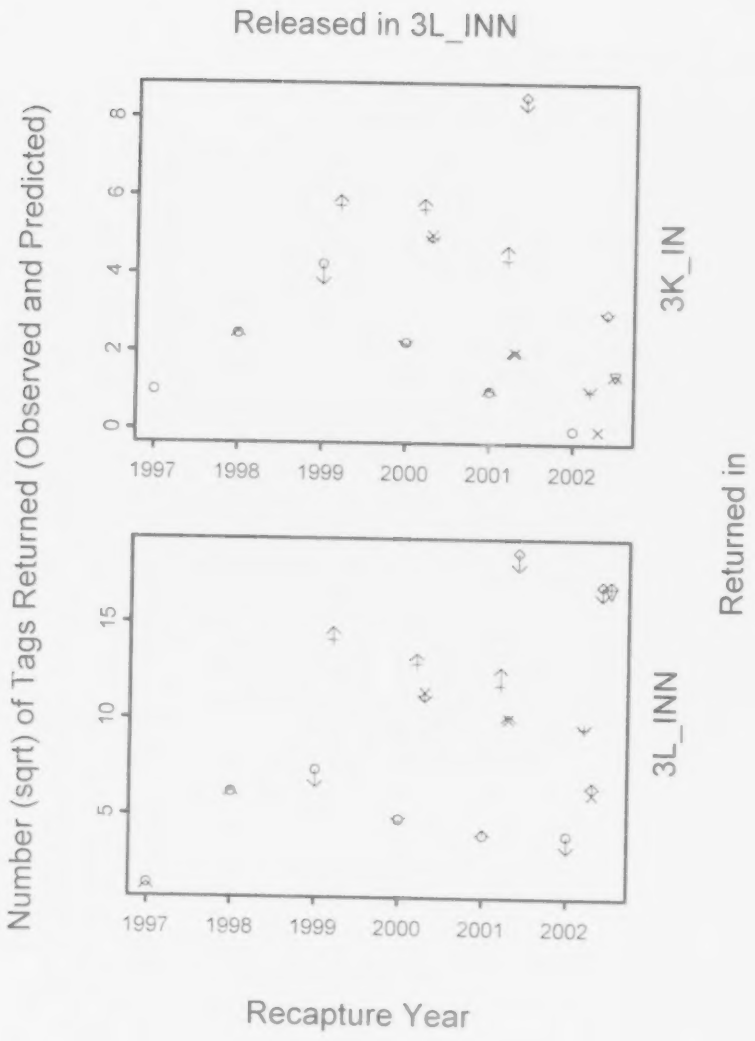

Figure 48: Annual total observed and predicted tag-recaptures for each release year in 3L_INN. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

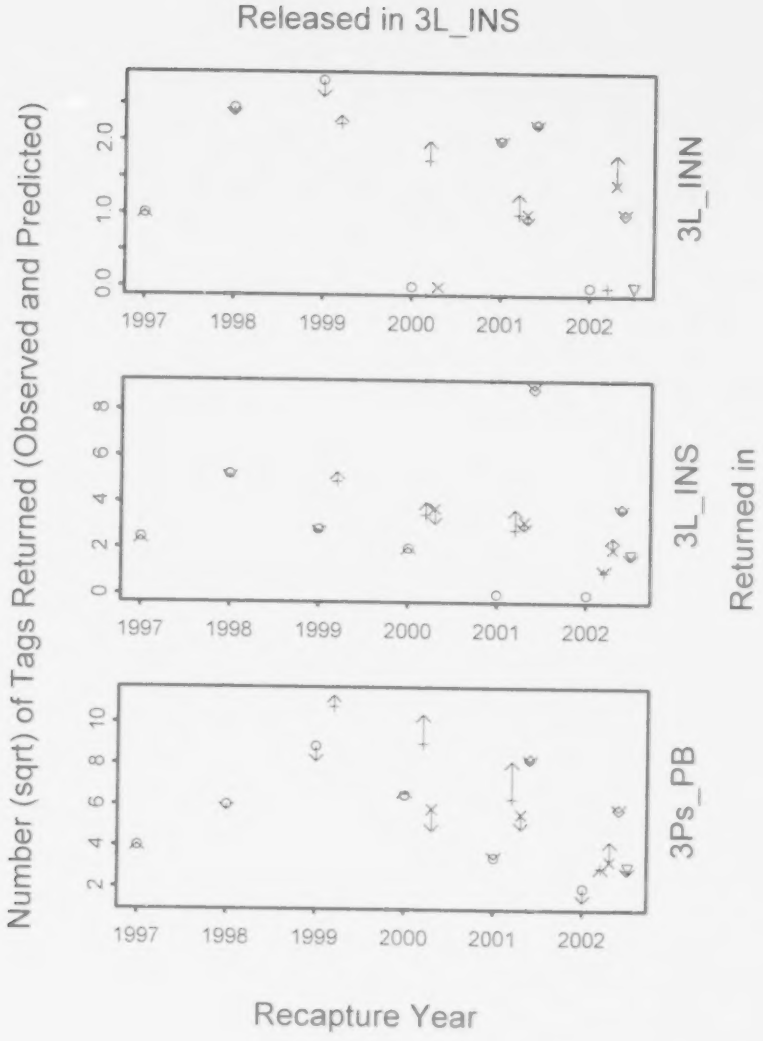

Figure 49: Annual total observed and predicted tag-recaptures for each release year in 3L_INS. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

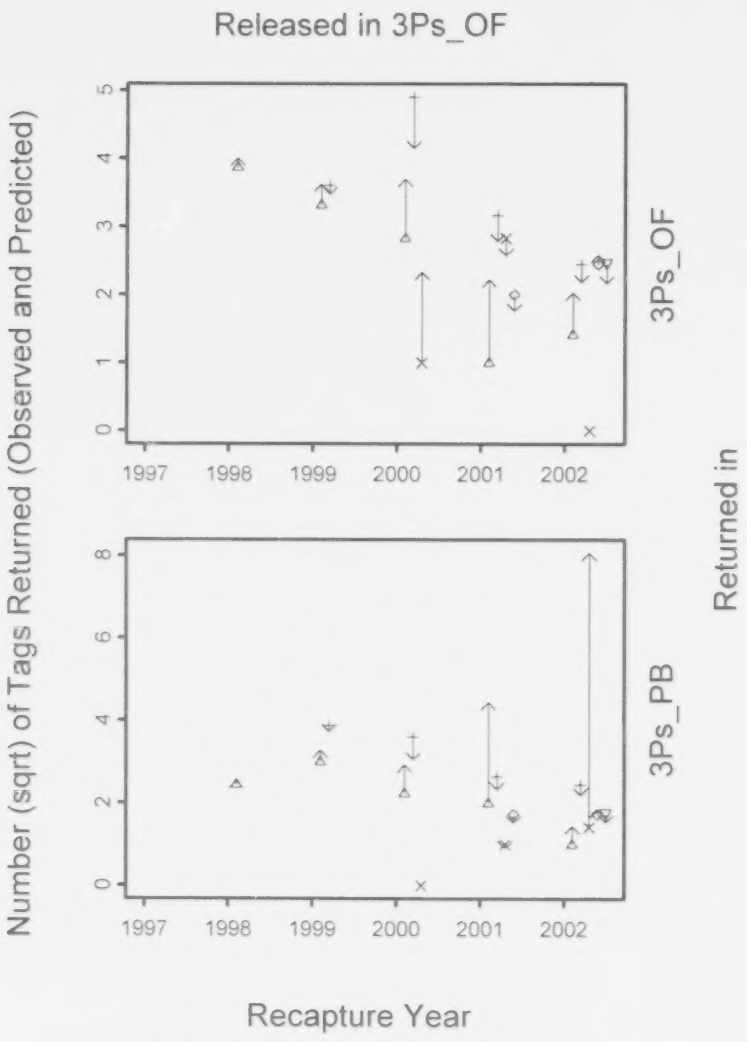

Figure 50: Annual total observed and predicted tag-recaptures for each release year in 3Ps_OF. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

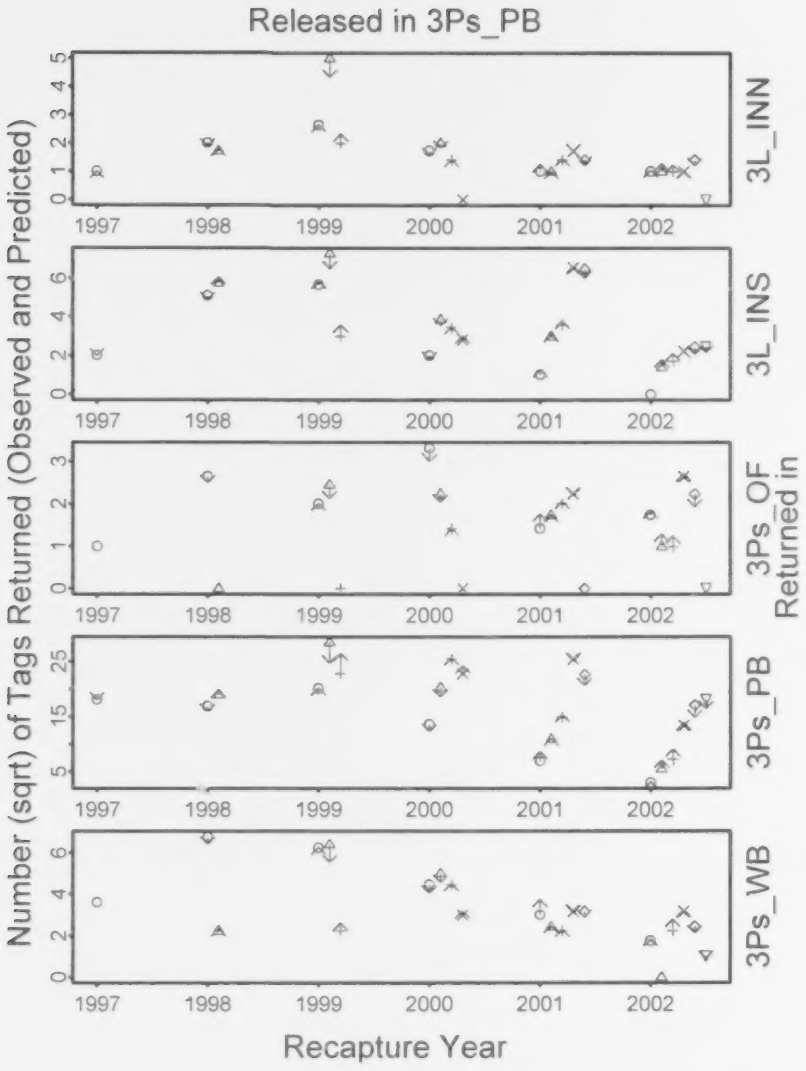

Figure 51: Annual total observed and predicted tag-recaptures for each release year in 3Ps_PB. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

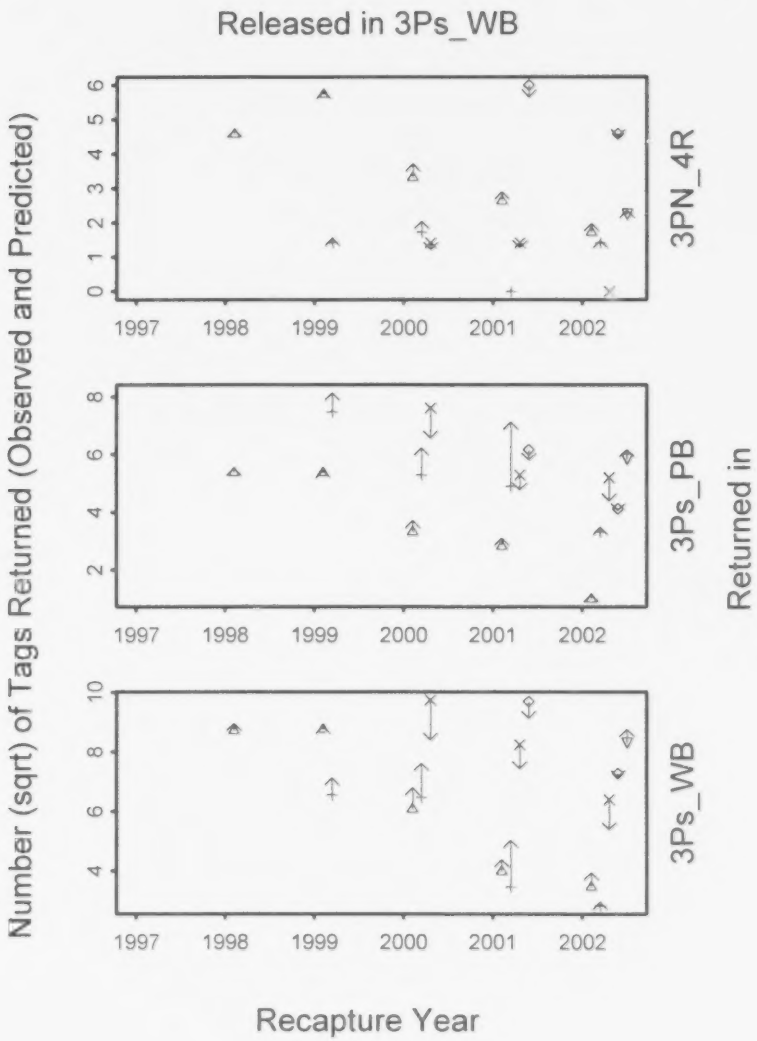

Figure 52: Annual total observed and predicted tag-recaptures for each release year in 3Ps_WB. The arrows point from the observed (shown as symbols) to the predicted. The symbols denote release years: $\circ \equiv 1997$, $\triangle \equiv 1998$, $+ \equiv 1999$, $\times \equiv 2000$, $\diamond \equiv 2001$, $\triangledown \equiv 2002$.

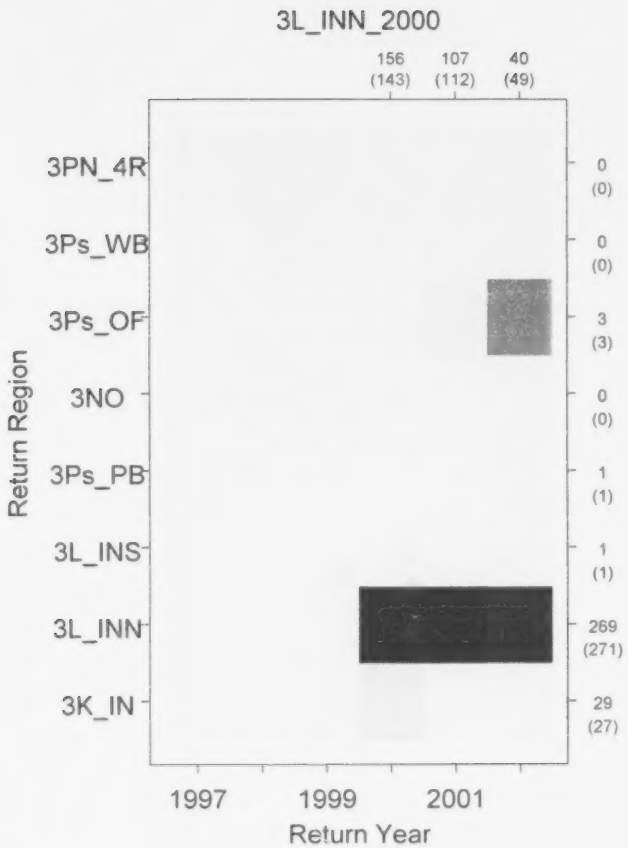

Figure 53: Annual (x-axis) estimates of the probability of occurrence in each region (y-axis). Dark shading indicates a high probability. The release region and year are shown at the top of the figure. The observed and model-predicted (parentheses) number of tag-recaptures is shown on the right hand side (regional totals) and top side (annual totals).

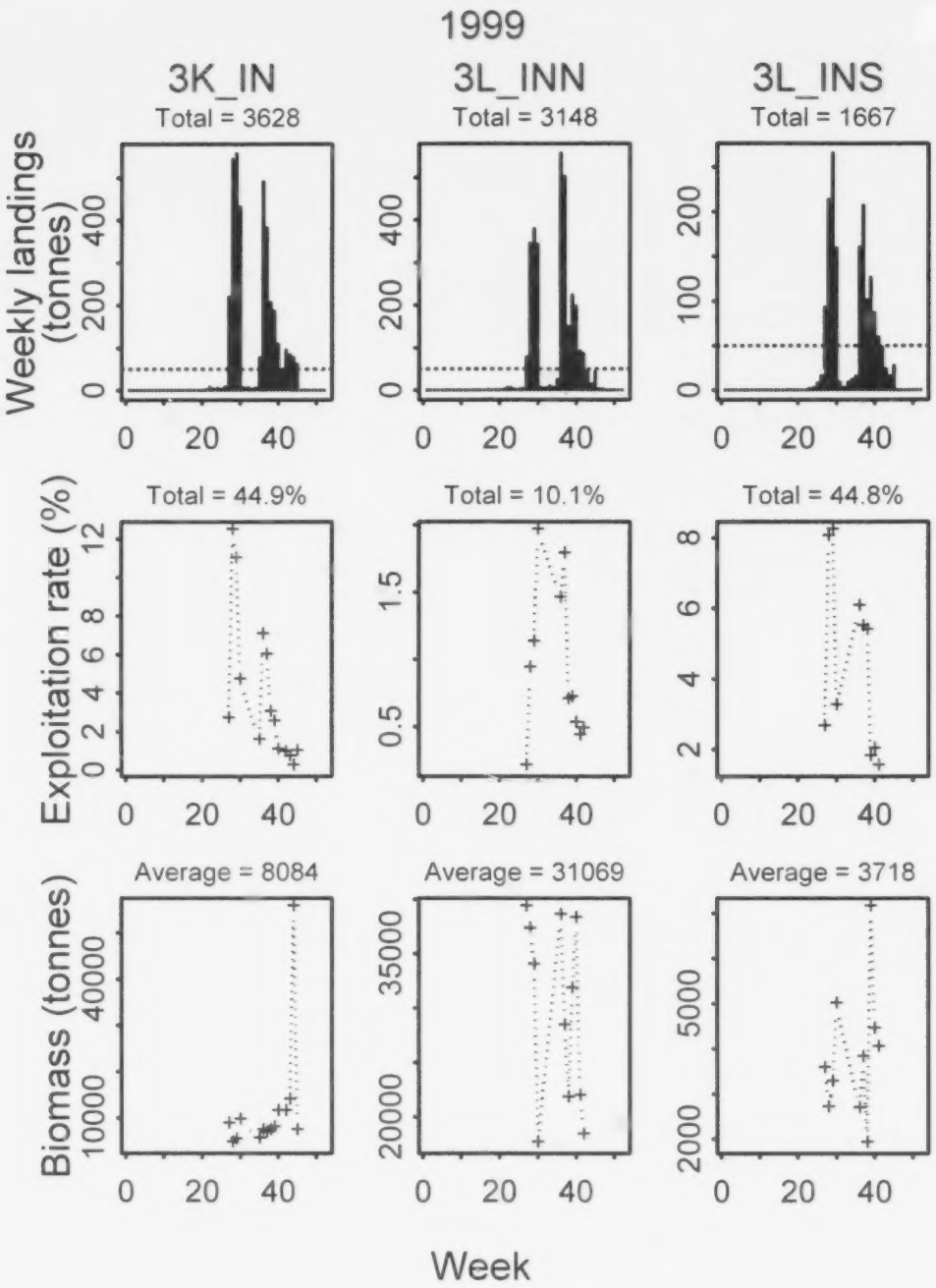

Figure 54: Estimates of total exploitation rates and biomass of cod in 3KL during 1999 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

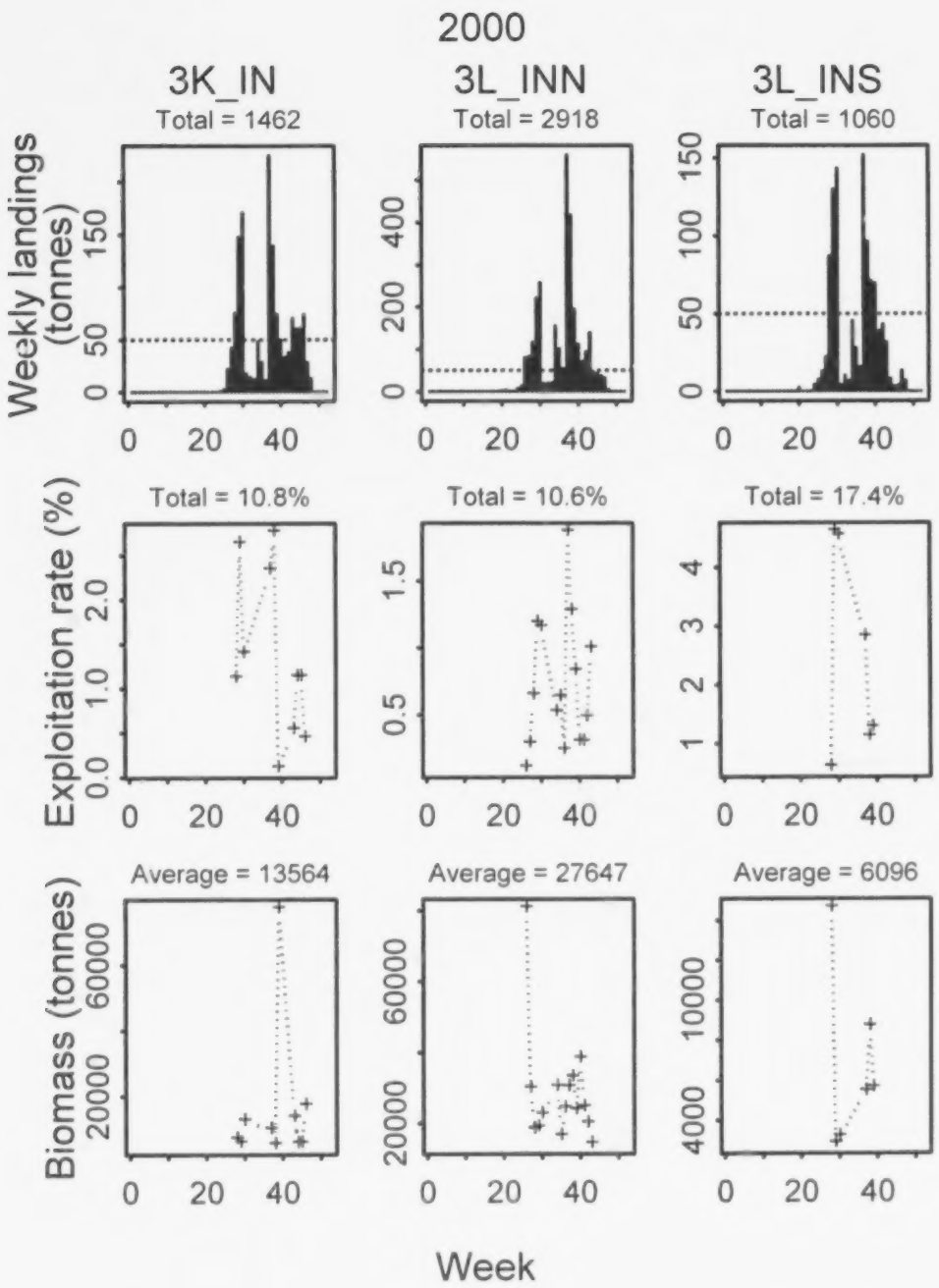

Figure 55: Estimates of total exploitation rates and biomass of cod in 3KL during 2000 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

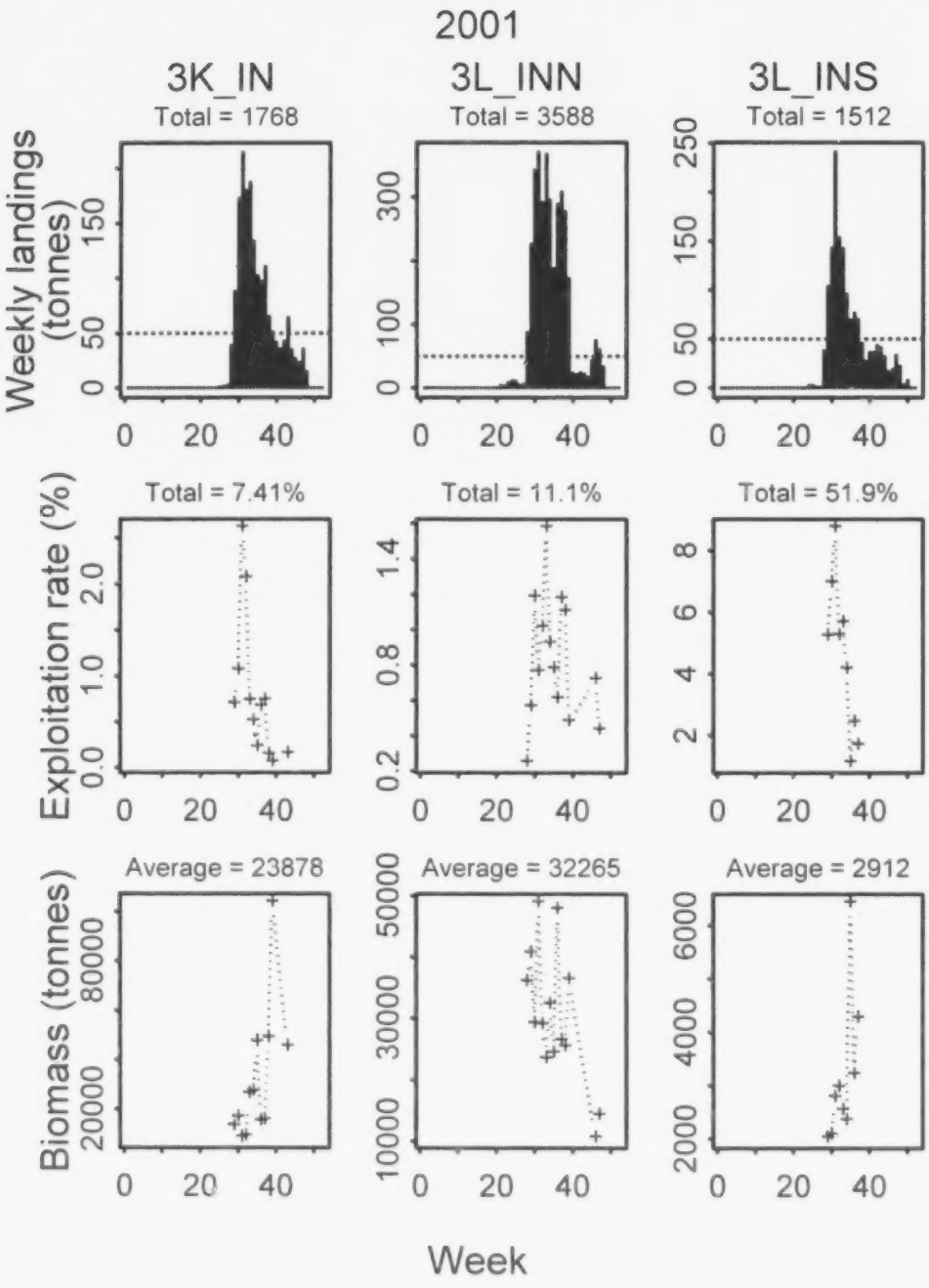

Figure 56: Estimates of total exploitation rates and biomass of cod in 3KL during 2001 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

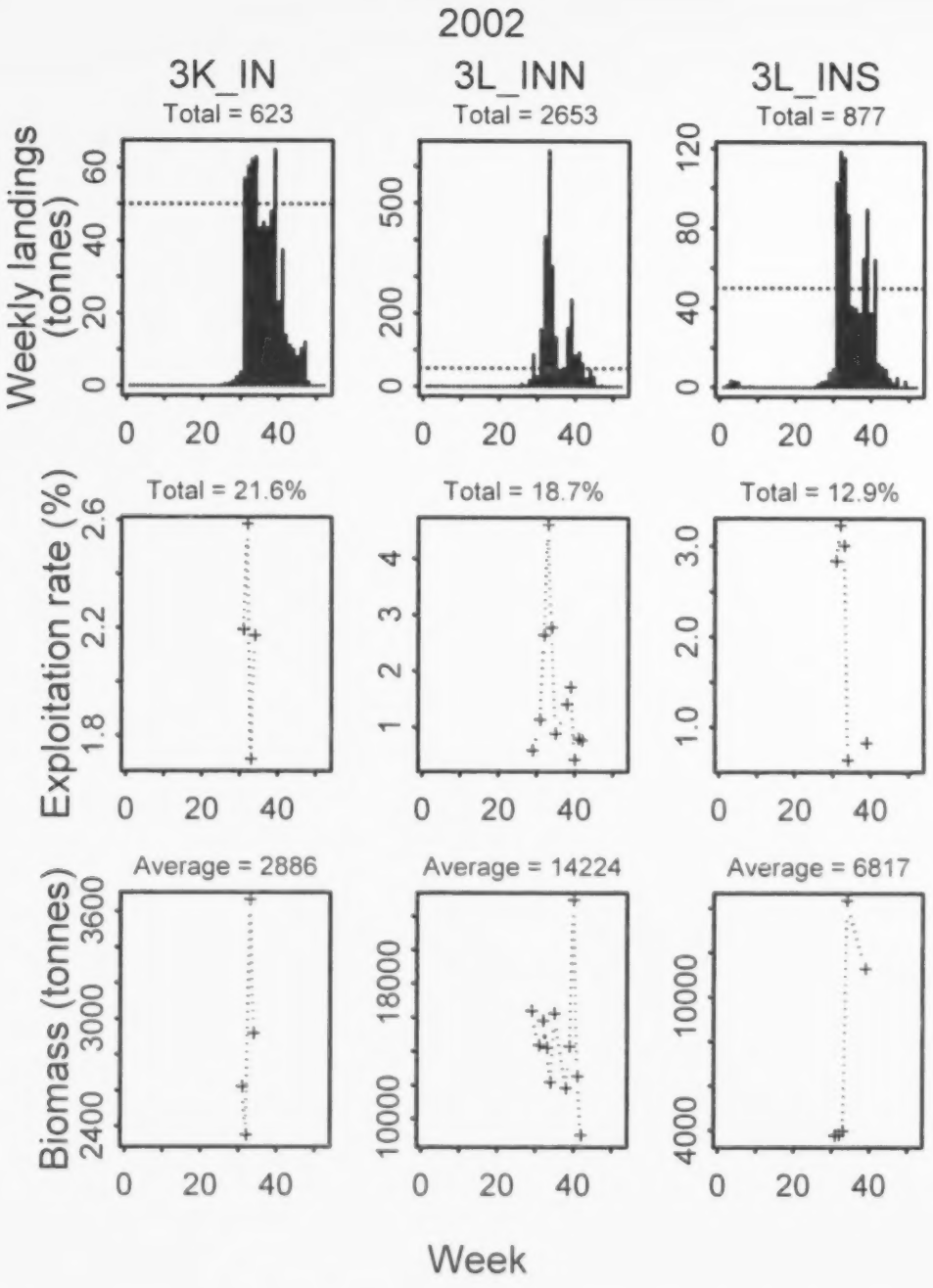

Figure 57: Estimates of total exploitation rates and biomass of cod in 3KL during 2002 for weeks in which at least 50 tonnes of cod were landed. The dotted line in the top panel shows the 50 tonne cut-off. The biomass and exploitation rate averages at the top of the middle and bottom panels are described in the text.

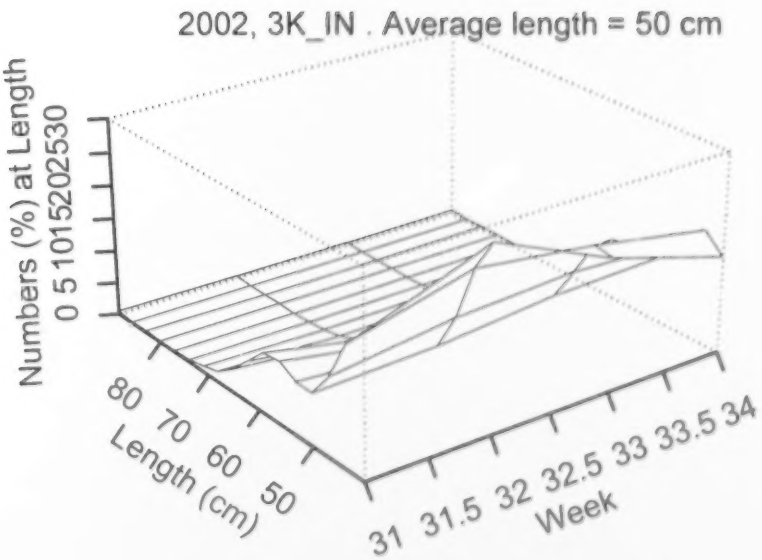

Figure 58: Estimated 2002 length composition (%) of the exploited population in 3K_IN for weeks in which at least 50 tonnes were landed. Lengths are grouped into 3 cm intervals. A plus group is used for lengths > 90 cm.

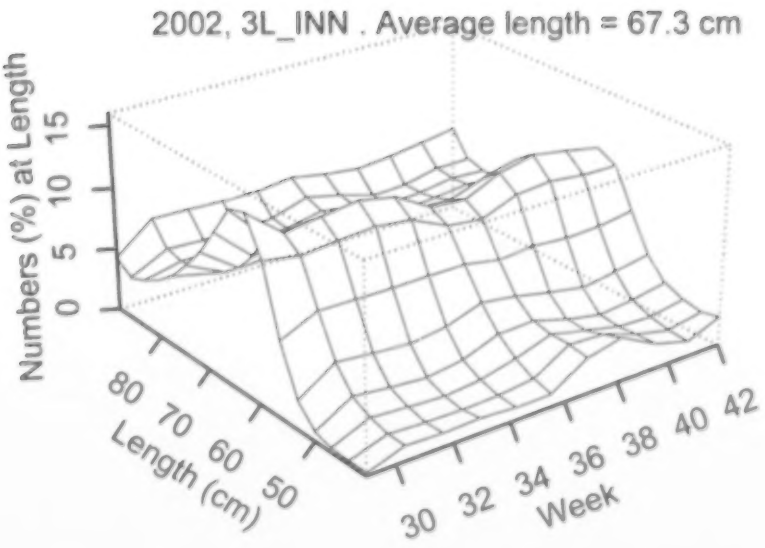

Figure 59: Estimated 2002 length composition (%) of the exploited population in 3L_INN for weeks in which at least 50 tonnes were landed. Lengths are grouped into 3 cm intervals. A plus group is used for lengths > 90 cm.

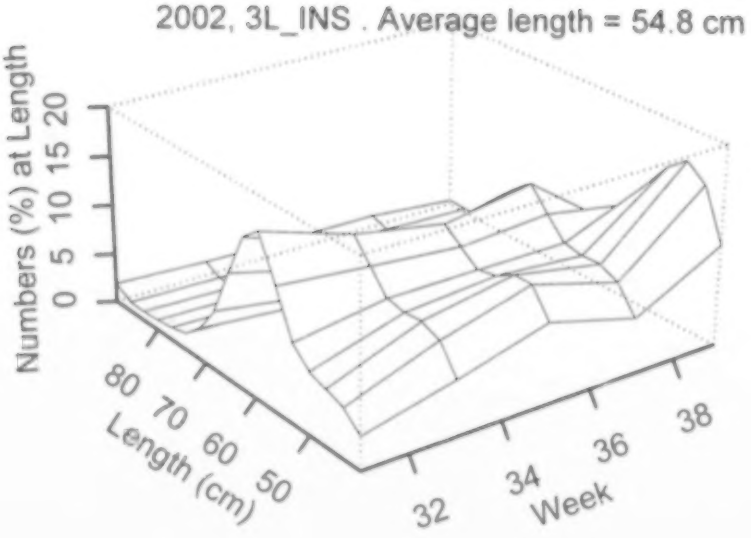

Figure 60: Estimated 2002 length composition (%) of the exploited population in 3L_INS for weeks in which at least 50 tonnes were landed. Lengths are grouped into 3 cm intervals. A plus group is used for lengths > 90 cm.